Changes in sediment accumulation rates within NW Mediterranean submarine canyons caused by bottom trawling activities

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Abstract

The disturbance of the marine sedimentary environments by commercial bottom trawling is a matter of concern. The direct physical effects of this fishing technique include scraping and ploughing of the seabed and increases of the near-bottom water turbidity by sediment resuspension. However, the quantification of the sediment that has been resuspended by this anthropogenic activity over the years and has been ultimately transferred along and across the margin remains largely unaddressed. The analysis of sediment accumulation rates from sediment cores collected along the axes of several submarine canyons in the Catalan margin (northwestern Mediterranean) has allowed to estimate the contribution of bottom trawling to the present-day sediment dynamics. ^{210}Pb chronologies, occasionally supported by ^{137}Cs dating, indicate a rapid increase of sediment accumulation rates since the 1960-70s, along with a strong impulse in the industrialization of the trawling fleets of this region. Such increase has been associated to the enhanced delivery of sediment resuspended by trawlers from shelf and upper slope trawling grounds towards submarine canyons, as a consequence of the rapid technical development at that time, in terms of engine power and gear size. This change has been observed in La Fonera (or Palamós) Canyon (one of the most prominent canyons of the region) at depths greater than 1700 m, while in other canyons not so deeply incised it is restricted to shallower regions (~1000 m in depth) closer to fishing grounds. Two sampling sites from La Fonera and Foix submarine canyons that exhibited high sediment accumulation rates (0.6-0.7 cm y^{-1}) were revisited several years after the first chronological analyses. These two new cores revealed a second and even more significant increase of sediment accumulation rates in both canyons which occurred circa 2000 and reached values higher than 2 cm y^{-1}. This second change at the beginning of the 21st century has been attributed to a preferential displacement of the trawling fleet towards slope fishing grounds surrounding submarine canyons, and to new technical improvements in trawling vessels, presumably related to subsidies and aids provided by the European Commission to the fishing industry.

Introduction

Bottom trawlers are commercial fishing vessels actively pulling nets along the seafloor with the aim of capturing fish and other marine species for human consumption or other industrial uses. Bottom trawling is carried out worldwide and its depth range has progressively expanded during the last years, from shelf and coastal environments towards deep-sea regions (Morato *et al*., 2006). The Catalan continental margin (NW Mediterranean) has supported an important bottom trawling activity during decades, currently reaching down to 800-900 m water depth. Deep-sea trawling in this region is mainly targeting the highly priced blue and red shrimp *Aristeus antennatus* (Risso, 1816), whose life cycle is closely related to submarine canyons environments (Sardà *et al*., 1994).

Bottom trawling poses many biological and physical impacts in the marine environment, and has been identified as a major force of seafloor disturbance by remobilizing and resuspending sediments, inducing the formation of nepheloid layers and sediment-laden flows, and by causing major changes in the morphology of continental slopes (Puig *et al*., 2012; Martín *et al*., 2014c). The trawling-induced resuspended sediment particles can be intercepted by submarine canyons and transported down-canyon, thus increasing sediment fluxes in deeper canyon regions.

An early study conducted in La Fonera (or Palamós) Canyon that analyzed a sediment core collected in the lower canyon axis, at 1750 m depth, documented a doubling of the sedimentation rate after the 1970s. Parallel analysis of historical fisheries data revealed that the local trawling fleet rapidly increased in terms of engine power during the same time period, which led to propose that the new sediment accumulation trend was a consequence of the enhancement of trawling-induced sediment resuspension and transport towards the lower canyon reaches (Martín *et al*., 2008).

To validate the hypothesis of a sedimentary regime shift caused by trawling activities in the Catalan margin, and to provide a broader view of this phenomenon at a margin-scale, several sediment cores taken from submarine canyons have been recently analyzed, including new cores from previously studied sites in La Fonera Canyon (Martín *et al*., 2008), and in Foix Canyon (Sánchez-Cabeza *et al*., 1999). Here we report the main results derived from this new coring effort and discuss the observed changes in sediment accumulation rates.

Methods

A KC Denmark A/S 6-tube (inner diameter 9.4 cm; length 60 cm) multicorer was used to collect undisturbed surface sediment cores along the axis of several submarine canyons incised in the Catalan margin (Fig. 1A). These cores were obtained during the past four years in several oceanographic cruises onboard the RV *García del Cid*.

In May 2011, a sediment core was collected in La Fonera (Palamós) Canyon (PC) at 1820 m water depth, 1.5 km away from the core analyzed in the same canyon region by Martín *et al*. (2008). In July 2012, three sediment cores were collected in Arenys Canyon (AC) at 1074 m, 1410 m and 1632 m water depth, respectively. During the same cruise, two other sediment cores were obtained in Besòs Canyon (BC) at 1238 m and 1487 m water depth. This submarine canyon was revisited in September 2014 to collect a shallower core at 810 m water depth. In October 2013, a sediment core was obtained at 865 m water depth in Foix Canyon (FC), close to the location where a former core was collected in 1993 and studied by Sánchez-Cabeza *et al*. (1999).

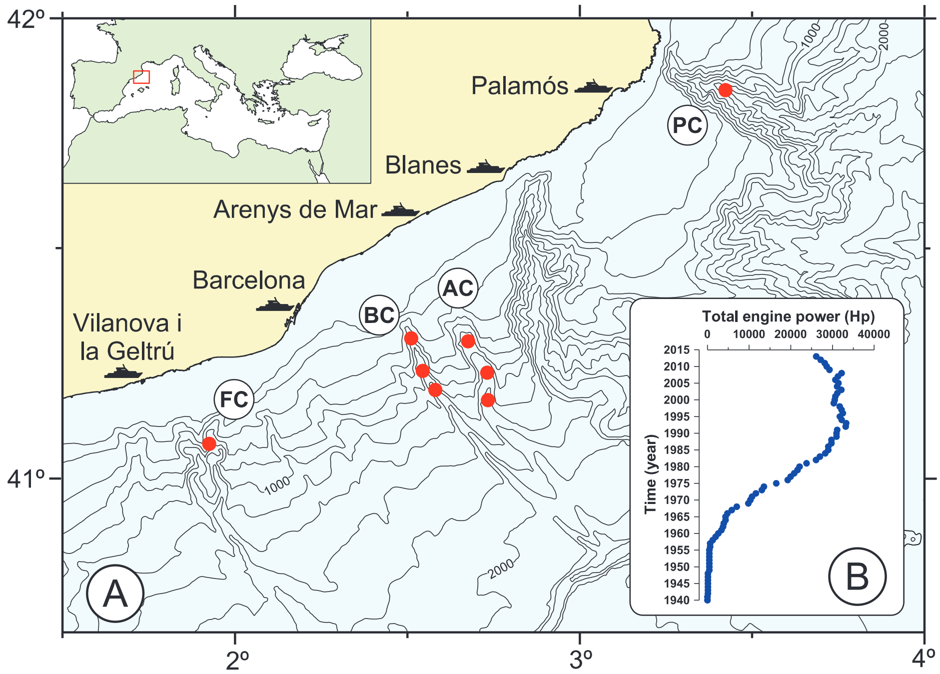

Figure 1. **A**: Bathymetric map of the Catalan margin showing the submarine drainage network and the major fishing harbors of this region (black ships). Sediment coring (red dots) was conducted at the axes of La Fonera, also known as Palamós Canyon (PC), Arenys Canyon (AC), Besòs Canyon (BC) and Foix Canyon (FC). Bottom trawling activities on this margin are conducted on a daily basis (excluding weekends and local holidays) on the shelf and upper continental slope, including submarine canyon rims and axes, down to 800-900 m water depth. **B**: Plot showing the evolution over time of the official total engine power (sum of the horsepower of all trawlers) of the major fishing harbors shown in the map. Note the rapid increase that occurred during the 1960-70s.

Sediment cores were sliced on-board at 1 cm intervals and the sections obtained were freeze-dried for further analysis. For the purpose of this document, only ^{210}Pb and ^{137}Cs activities are presented, from which sediment accumulation rates over the last 100-150 years have been derived. The concentrations of ^{210}Pb were determined by alpha-spectroscopy following Sánchez-Cabeza *et al*. (1998). ^{137}Cs concentrations were measured by γ-counting of dried, homogenized samples in calibrated geometries for $2\text{-}3\cdot10^5$ s on a high purity intrinsic germanium detector. Sediment accumulation rates were calculated based on a one-dimensional, steady-state constant ^{210}Pb flux/constant sedimentation model constrained by the ^{137}Cs concentration profiles (Masqué *et al*., 2003).

Historical data of the characteristics of the trawling fleet operating in the region studied were obtained from official bulletins and databases provided by the Spanish Ministry of Agriculture, Livestock and Environment. The temporal evolution of the total engine power (sum of the horsepower of all trawlers) of the major harbors of this area (black ships in Fig. 1A) is shown in Fig. 1B. Total engine power is considered to be a reliable proxy for the size and weight of the gear that a boat can tow, as well as for working depth and haul duration, indicative of the capacity to resuspend bottom sediments (Martín *et al*. 2014c).

Results and Discussion

Arenys Canyon

The sediment cores collected in Arenys Canyon were previously studied by Toro (2013) and are presented in Fig. 2. The results show a constant and fairly similar sediment accumulation rate at the two deeper stations, accounting for 0.057 ±- 0.001 g $cm^{-2}\cdot y^{-1}$ (0.082 ± 0.002 cm y^{-1}) at 1410 m water depth and 0.066 ± 0.001 g $cm^{-2}\cdot y^{-1}$ (0.096 ± 0.002 cm y^{-1}) at 1632 m water depth. However, two clear sediment accumulation rates were observed at the shallower site: the lower part of the sediment core (13-20 cm) displays an accumulation rate of 0.054 ± 0.002 g cm^{-2}·y^{-1} (0.063 ± 0.003 cm y^{-1}), while the surface sediment unit (0-14 cm) has a higher accumulation rate of 0.203 ± 0.009 g cm^{-2}·y^{-1} (0.332 ± 0.015 cm y^{-1}). The sedimentation model estimates that the change in the accumulation rates took place during the 1960-70s.

In this submarine canyon, the change in sediment accumulation rates attributable to the resuspension by trawling activities is only recorded in the shallower core closer to fishing grounds, where sedimentation rates have increased five times with regard to the natural (pre-1960-70s) ones. The constant and similar sedimentation rates observed in the two deeper cores located offshore from the trawled slope regions suggest that the trawling-resuspended sediment in this canyon region is mainly transported along-margin, with limited off-shore dispersal. The morphological characteristics of the Arenys Canyon, with a wide canyon axis and absence of a defined canyon head incised on the shelf edge, may favor this behavior.

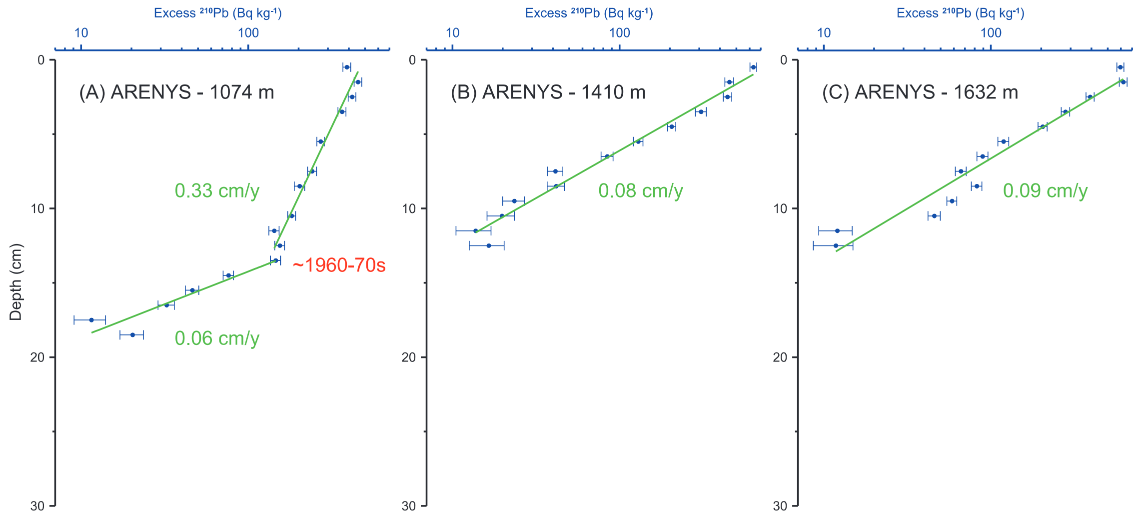

Figure 2. Excess ^{210}Pb activity profiles and sedimentation rates of the three sediment cores collected along the Arenys canyon axis in July 2012. See core locations in Figure 1A.

Besòs Canyon

The two deeper cores collected in July 2012 in the Besòs canyon axis were previously studied by Juan-Díaz and Paradis (2014) and are presented here together with a shallower core collected in September 2014. At the deeper site, 1487 m water depth (Fig. 3 C), the sediment core displays an apparent surface mixed layer (SML) and a constant sediment accumulation rate down to 18 cm of 0.065 ± 0.002 g cm^{-2}·y^{-1} (0.091 ± 0.002 cm y^{-1}). This sedimentation rate is in agreement with those found in the two deeper cores from the neighboring Arenys Canyon (Figs. 1A and 2). The excess ^{210}Pb concentration profile from the sediment core collected at 1238 m water depth (Fig. 3 B) is more complex. At the lower part of the core (20-26 cm), a constant accumulation rate of 0.083 ± 0.006 g cm^{-2}·y^{-1} (0.117 ± 0.009 cm y^{-1}) is observed. Above, a portion of the sediment core (15-19 cm) shows an anomalous excess ^{210}Pb activity profile denoting a non-steady-state sedimentation, and above it (5-14 cm) the previous sediment accumulation rate is reestablished, accounting for 0.081 ± 0.005 g cm^{-2}·y^{-1} (0.125 ± 0.008 cm y^{-1}). Finally, in the uppermost part of the sediment core, an apparent SML of 4 cm is observed. In general, a mean sedimentation rate of ~0.12 cm y^{-1} seems to prevail through time at this canyon site, although it was disrupted during a certain period by the arrival of sediments at a non-constant rate. The X-radiograph and grain-size analysis of this sediment core (not shown) do not suggest that this portion of the sedimentary column could be caused by a massive arrival of sediments in a single event (i.e., as a turbidite or debris flow). A possible explanation could be a transitory alteration of the natural fluxes by the onset of trawling activities in this submarine canyon, which affected this part of the canyon for a limited period of time, since the sedimentation model suggests that this disruption occurred circa the 1960-70s.

At the shallower canyon location, at 810 m water depth, one observes a clear change in sediment accumulation rates (Fig. 3A). The excess ^{210}Pb activity profile from this sediment core shows that the bottom part (30-50 cm) displays a constant accumulation rate of 0.34 ± 0.03 g $cm^{-2} \cdot y^{-1}$ (0.43 ± 0.03 cm y^{-1}) and that above this unit a non-steady-state sediment flux prevailed until present times. The sedimentation model indicates that this change occurred during the 1960-70s, in accordance with an alteration by bottom trawling activities of the natural sedimentation in the upper canyon reaches. Given the non-constant sediment flux in this upper portion of the sediment core, the accumulation rates could not be properly calculated, but if we integrate all the episodes that have constituted this sedimentary unit, taking into account the mass accumulated over the last 40-50 years, we obtain a mean sedimentation rate of 0.60-0.75 cm y^{-1}.

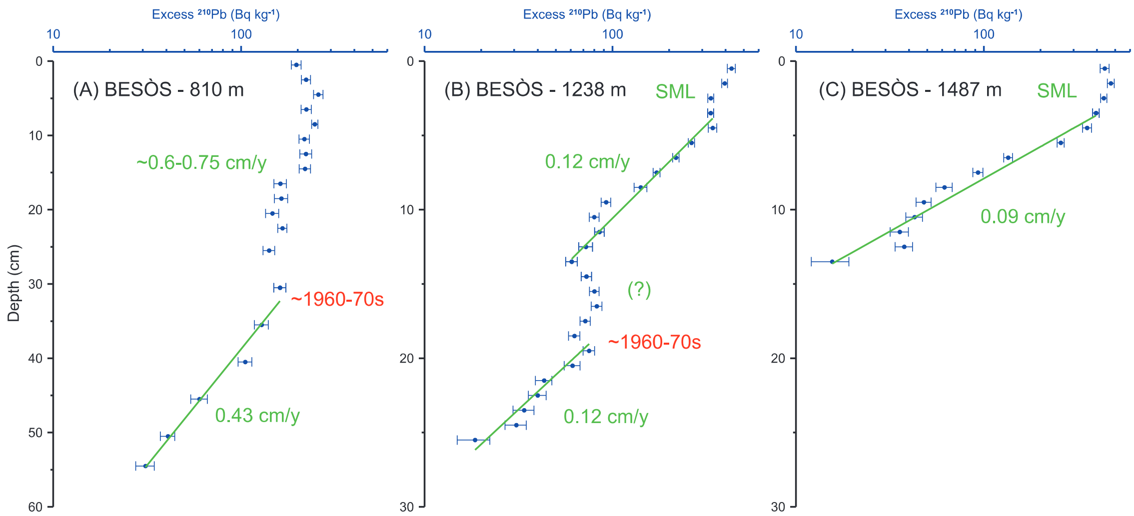

Figure 3. Excess ^{210}Pb activity profiles and sedimentation rates of the three sediment cores collected along the Besòs canyon axis in September 2014 (A) and in July 2012 (B and C). See core locations in Figure 1A.

La Fonera (Palamós) Canyon

The sediment core collected in 2002 in La Fonera canyon axis, at 1750 m water depth, recorded for the first time the post-1970s increase in the sedimentation rates linked to trawling activities (Martín *et al*., 2008). This core showed two contrasting sedimentary units: a deep unit without physical structures and a ^{210}Pb and ^{137}Cs derived sedimentation rate of 0.35 cm y^{-1} underlying a topmost sedimentary unit with a higher sedimentation rate, estimated at ~0.7 cm y^{-1}, as well as a well-preserved horizontal laminae. This increase in the accumulation rates and the preservation of physical structures in the sedimentary column was associated with the enhancement of trawling-induced sediment resuspension and transport towards deeper canyon reaches, observed to occur as sediment gravity flows funneled through tributary valleys on the canyon flanks (Palanques *et al*., 2006a; Martín *et al*., 2007). The excess ^{210}Pb and total ^{137}Cs activity profiles of this sediment core are shown in Fig. 4A.

In May 2011 a new sediment core was collected from a nearby canyon axis location at 1820 m water depth. The deepest layer at which ^{137}Cs was detected was at 44 cm, providing the ~1954 time marker, when this artificial radionuclide was first introduced to the environment as a consequence of atmospheric nuclear bomb testing. A broad increase of ^{137}Cs activity could be observed upwards, with two relative maxima at 39 and 36 cm depth, corresponding to the historical peak fallout around 1963 (Fig. 4B). From bottom to top, one can identify a section (47-37 cm) with a constant slope of the excess ^{210}Pb activity profile, denoting a steady-state accumulation of sediment that allowes calculating a rate of 0.20 ± 0.02 g cm^{-2} y^{-1} (0.25 ± 0.02 cm y^{-1}). From 36 cm depth to the sediment surface, the excess ^{210}Pb activity profile suggests a non-steady-state accumulation of sediment, presumably generated by a series of depositional events. The combination of the ^{210}Pb sedimentation model and the ^{137}Cs profile allows dates this change in the early 1970s. Taking into account the sediment thickness accumulated since that period, we obtain a mean sedimentation rate in the upper part of the core of ~1 cm y^{-1} (Fig. 4B).

To conduct a comparison between both cores, we considered that the regions of the two sediment cores where the slope of the excess ^{210}Pb vertical profile changes (i.e. due to a change in the sedimentation rates in the early 1970s), represent synchronous time horizons. Hence, in Fig. 4C the vertical axis of the core collected in 2002 was shifted 23 cm downwards to confront the sharpest ^{210}Pb discontinuities in both profiles. The synchrony of the change in sedimentation rates is further supported by the occurrence, at consistent depth intervals, of the ^{137}Cs maxima and the deepest appearance of detectable ^{137}Cs in the profile. Also, ^{210}Pb concentrations at the depths confronted in Fig. 4C are consistent with the radioactive decay of this radionuclide ($T_{1/2}$= 22.3 y) and with the nine years elapsed between coring operations.

Even though the pre-1970s sedimentation rate in the 2011 core has been estimated in 0.25 cm y^{-1} and the post-1970s layer accounts for an average rate of ~1 cm y^{-1}, the simple comparison with the 2002 core suggests that an enhancement of sediment accumulation might have occurred in this submarine canyon during the last decade. The 23 cm of sediment that appear to have been accumulated in nine years would represent a recent sedimentation rate of ~2.5 cm y^{-1}, an order of magnitude higher than the pre-1970s values (Fig. 4C).

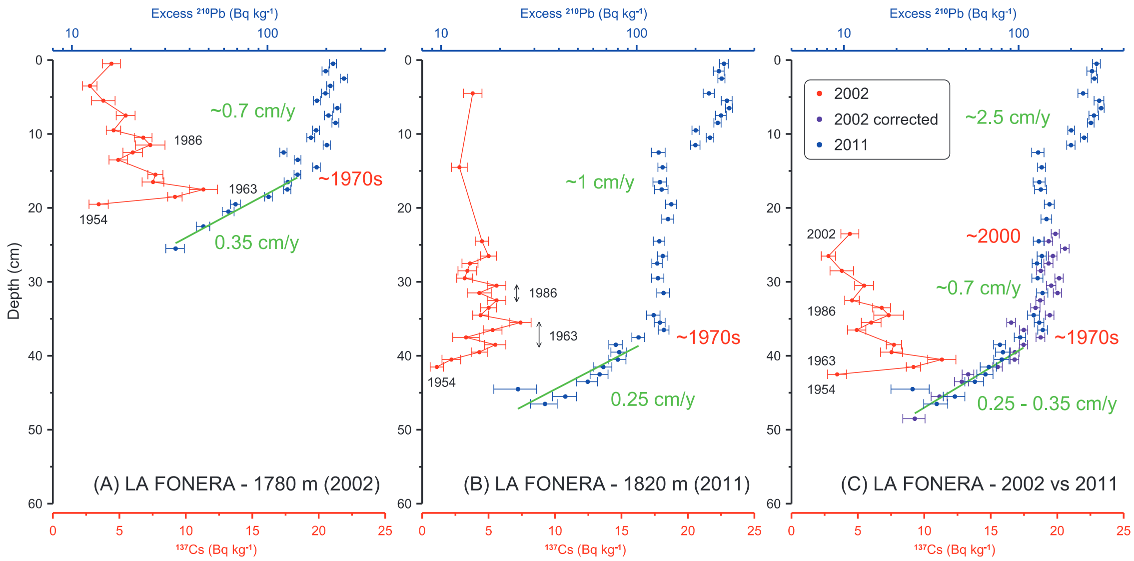

Figure 4. Excess ^{210}Pb and total ^{137}Cs activity profiles of sediment cores collected from the lower La Fonera (Palamós) canyon axis in 2002 and 2011. A doubling of the sediment accumulation rates after the 1970s was observed in 2002 by Martín *et al.* (2008). The core collected in 2011 confirms such a change, but the comparison between both cores suggests a more rapid change in sediment accumulation rates during the last decade.

Foix Canyon

In October 2013, a sediment core was obtained in the Foix canyon axis at 865 m water depth, revisiting the location of a previous core collected in April 1993 and analyzed by Sánchez-Cabeza *et al.* (1999). This allowed the study of the evolution of the sediment accumulation rates at this site with a time difference of 20 years (Fig. 5).

The 1993 sediment core showed a clear ^{137}Cs concentration profile, with the 1954 time marker occurring at 25 cm, the 1963 fallout peak at 23 cm, and the 1986 Chernobyl accident peak at 7 cm (Fig. 5A). The excess ^{210}Pb activity profile showed an apparent SML of 5 cm and a fairly constant slope that corresponded to a sediment accumulation rate of 0.51 ± 0.02 g cm^{-2} y^{-1} (0.58 ± 0.3 cm y^{-1}) (Sánchez-Cabeza *et al.*, 1999).

In the 2013 sediment core, analyzed by Juan-Díaz and Paradis (2014), ^{137}Cs was not measured and the horizon of supported ^{210}Pb was not reached (Fig. 5B). However, the same supported ^{210}Pb activity of the 1993 sediment core (30 ± 1 Bq·kg^{-1}) was assumed to reflect the excess ^{210}Pb activities. At the bottom of the 2013 sediment core anomalous values of excess ^{210}Pb activity were found and above them (43-23 cm) a constant ^{210}Pb slope allowed determining a unit with a sediment accumulation rate of 0.61 ± 0.04 g cm^{-2} y^{-1} (0.72 ± 0.04 cm y^{-1}). Above it, and up to the sediment surface, the ^{210}Pb slope increases considerably and accounted for a sediment accumulation rate of 1.6 ± 0.2 g cm^{-2} y^{-1} (2.2 ± 0.3 cm y^{-1}). The sedimentation model establishes this three-fold increase of sedimentation rates around year 2000 (Fig. 5B). This new change at the beginning of the 21st century is in agreement with the recent increase inferred in La Fonera Canyon after the comparison of the two available sediment cores (Fig. 4C).

The comparison between the two sediment cores collected 20 years apart in the Foix Canyon is shown in Fig. 5C. In this occasion, the excess ^{210}Pb activities from 1993 were corrected by theoretical decay until 2013, and both vertical profiles were overlapped by shifting the 1993 core 30 cm downwards. By doing so, the anomalous ^{210}Pb values at the bottom of the 2013 core coincided with similar anomalous values observed in the 1993 core around year 1963, at the level of the ^{137}Cs fallout peak. In fact, if the SML at the top of the 1993 core is not considered, two distinct ^{210}Pb slopes can be defined, being separated by these anomalous values. A top unit shows a sedimentation rate of 0.76 cm y^{-1} (considering that 23 cm were deposited in 30 years, from 1963 to 1993), which agrees with the 0.72 cm y^{-1} rate determined in the bottom part of the 2013 core; overlying a deeper unit with a lower sedimentation rate of 0.58 cm y^{-1} (Fig. 5C). Therefore, it seems that a subtle increase of sediment accumulation rates caused by bottom trawling activities may have also occurred in Foix Canyon during the 1960-70s, in accordance with the changes observed in other submarine canyons of the Catalan margin.

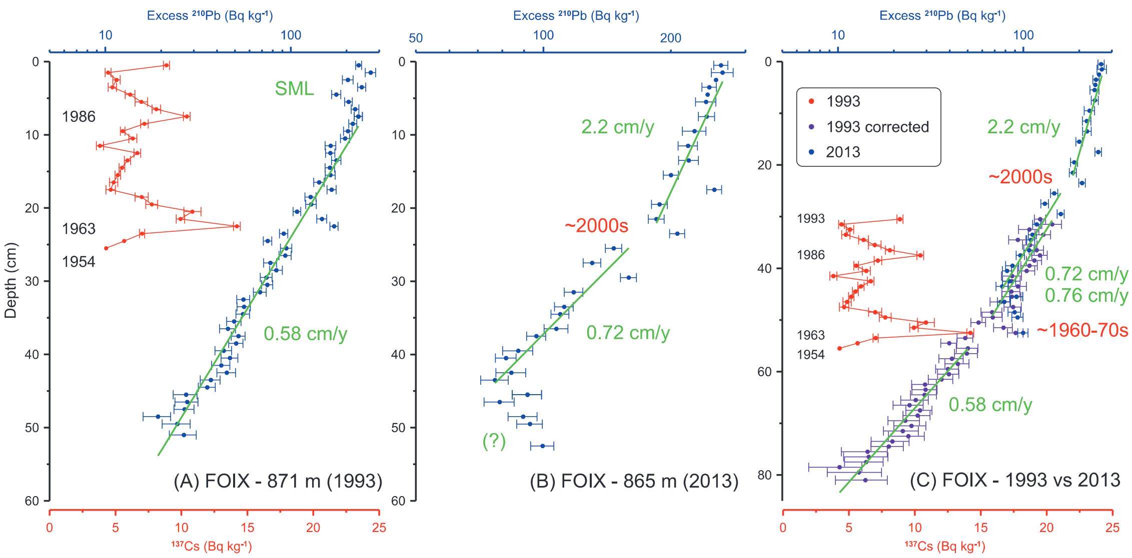

Figure 5. Excess ^{210}Pb and total ^{137}Cs activity profiles of the two sediment cores collected 20 years apart in the Foix canyon axis. A constant sediment accumulation rate was assumed in 1993 by Sánchez-Cabeza *et al.* (1999), while in the sediment core collected in 2013, a noticeable change in sediment accumulation rates was detected circa 2000. The combination of both cores without considering a SML in the 1993 one also suggests a subtle increase of sediment accumulation rates ~1960-70s.

Conclusions and prospects

The analysis of sediment accumulation rates from various sediment cores recently collected along the axes of several submarine canyons of the Catalan margin has evidenced that bottom trawling activities have altered the natural sedimentary dynamics in all studied sites since the 1960-70s. The resulting increase in sediment accumulation rates seems to be limited to canyon regions close to fishing grounds, while deeper areas remain unaffected as a consequence of a predominant along-margin transport of the trawled-induced resuspended particles.

In addition, an even more significant change in sedimentation rates has occurred in specific submarine canyons since the beginning of the 21st century, accounting for values >2 cm y^{-1}. Such enhanced sedimentation rates may seem in contradiction with the slight decrease in total power of the local trawling fleet obtained from the official databases. The reality is that ship-owners have been continuously introducing technical improvements in their trawlers (namely more powerful engines and larger gears), a practice that leaves no trace in the official reports. The official decreasing trend mainly reflects a reduction in the total number of vessels, since a large dismantling of trawlers has been occurring in the Catalan harbors since the 1990s, motivated by subsidies and aids provided by the European Commission to the fishing sector. However, even though the new constructed vessels are officially limited to <500 Hp, their real horsepower is generally much higher.

Together with the not declared increase in installed power, one must take into account that, over the last decades, the Catalan trawling fleet has evolved towards an increasing economic specialization and dependence in the *Aristeus antennatus* fishery (Alegret and Garrido, 2008). This may also contribute to the significant increase of sediment accumulation rates within specific submarine canyons, as a result of progressive concentration of the fishing effort over this species and the subsequent increase in trawling-induced resuspension (and relocation) of sediments surrounding submarine canyons.

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