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Key Points:
- Sediment accumulation rates on continental margins can be altered by trawling activities
- Submarine canyons can host anthropogenic sedimentary depocenters along their axes

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Increasing sediment accumulation rates in La Fonera (Palamós) submarine canyon axis and their relationship with bottom trawling activities

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Abstract Previous studies conducted in La Fonera (Palamós) submarine canyon (NW Mediterranean) found that trawling activities along the canyon flanks cause resuspension and transport of sediments toward the canyon axis. ^{210}Pb chronology supported by ^{137}Cs dating applied to a sediment core collected at 1750 m in 2002 suggested a doubling of the sediment accumulation rate since the 1970s, coincident with the rapid industrialization of the local trawling fleet. The same canyon area has been revisited a decade later, and new data are consistent with a sedimentary regime shift during the 1970s and also suggest that the accumulation rate during the last decade could be greater than expected, approaching ~2.4 cm yr^{-1} (compared to ~0.25 cm yr^{-1} pre-1970s). These results support the hypothesis that commercial bottom trawling can substantially affect sediment dynamics and budgets on continental margins, eventually initiating the formation of anthropogenic depocenters in submarine canyon environments.

1. Introduction

The growing capacity of humans to redistribute significant amounts of materials and modify the shape of the Earth is well established on land, while similar observations are only recently being reported for the deep sea. As terrestrial particles are delivered to the sea from river discharge and land runoff, they tend to accumulate near the shore by gravitational settling, forming ephemeral sedimentary deposits that can be remobilized until reaching a permanent repository in deeper waters [*Nittrouer and Wright*, 1994; *Walsh and Nittrouer*, 2009]. In present times, human activities such as river damming and land use changes have significantly modified the quantity and rate of terrestrial inputs into the sea [*Syvitski et al.*, 2005]. Bottom trawling, a common method of industrial fishing worldwide, has also been identified as an important vector of change in sedimentary dynamics on continental margins [*Jones*, 1992; *Martín et al.*, 2104a]. Fishing gear dragged along the ocean bottom resuspends sediments, which induces the formation of nepheloid layers and sediment-laden flows. This resuspension has the potential to cause sediment erosion and major changes in the morphology of continental slopes [*Puig et al.*, 2012; *Martín et al.*, 2104b]. Given the mobility, persistence, and wide geographical distribution of bottom trawling, this fishing practice could lead to changes in regional sedimentary budgets, transforming depositional areas into sediment-starved regions and promoting the formation of new sedimentary depocenters where the anthropogenically remobilized sediments accumulate.

This study was conducted in La Fonera (or Palamós) submarine canyon (NW Mediterranean Sea). The flanks of the canyon have been exploited by a trawling fishery targeting blue and red shrimp (*Aristeus antennatus*) for several decades in a depth range of ~450–800 m (Figure 1). Previous studies showed that sediments resuspended by the trawling activities are transported downslope, from the fishing grounds toward the canyon interior, as bottom-arrested sediment gravity currents [*Palanques et al.*, 2006; *Martín et al.*, 2014]. This submarine canyon is considered to be representative of most of the canyons incising the NW Mediterranean continental margin [*Canals et al.*, 2013], which are subjected to a similar intensity of trawling [*Puig et al.*, 2012]. Enhanced particle fluxes collected by moored sediment traps and attributed to bottom trawling have also been reported in Foix Canyon [*Puig and Palanques*, 1998] and Blanes Canyon [*Lopez-Fernandez et al.*, 2013].

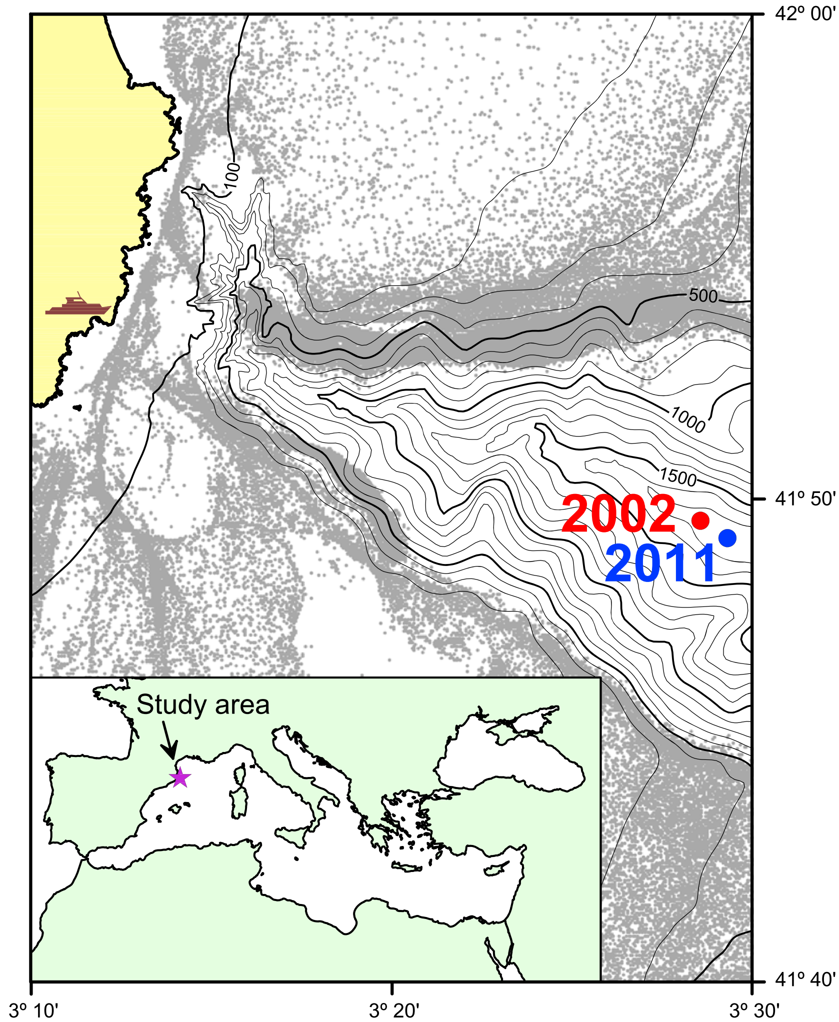

Figure 1. Bathymetric chart of La Fonera (Palamós) submarine canyon head showing the location of the sediment cores extracted in 2002 and 2011. The main trawling grounds are outlined by clouds of grey points, corresponding to the 2007–2010 Vessel Monitoring System (VMS) positions from the trawlers operating in Palamós harbor (brown ship).

Three sediment cores collected at 400, 1200, and 1750 m depth along La Fonera canyon axis in 2002, indicated recent changes of sedimentary trends caused by bottom trawling activities [*Martín et al*., 2008]. A twofold increase in the sediment accumulation rates concurrent with a change in the sediment core X-radiograph from bioturbated texture to well-preserved sedimentary layering was observed at the deepest site. The age model indicated that the purported shift of sedimentary regime took place during the 1970s. Historical fisheries data revealed that the engine power of the local trawling fleet had greatly increased during the same time period, leading to the proposition that the enhanced accumulation trend was a consequence of trawling-induced sediment resuspension and transport toward the lower canyon reaches.

Here we present results from a recently (2011) collected sediment core from the same deep canyon area as that discussed in *Martín et al*. [2008]. The main goals of this new paper are to test the hypothesis of a trawling-induced sedimentary regime shift in the lower canyon axis since the 1970s and to study the evolution of this change in recent years linked to the technological progress of the fishery sector.

2. Data and Methods

In May 2011, a hydraulically damped KC multicorer equipped with six acrylic tubes was used to collect a sediment core from the axis of La Fonera Canyon, at 1820 m depth (Figure 1). Two undisturbed sediment tubes were selected for analysis. One of them was subsampled on board by taking 1 cm thick slices along its 47 cm length. Subsamples were immediately frozen at −20°C and afterward lyophilized in the laboratory. The second was subsampled with a rectangular PVC vertical slab for its imaging using a Sedecal APR-VET veterinary-specific X-ray system and a medical SOMATOM Sensation computed tomography (CT) scanner.

Dry bulk density was determined as the ratio between dry weight (corrected for salt content) and sample volume. Grain size distribution was determined on dry samples after treatment with H_2O_2 and $(NaPO_3)_6$, using a Horiba Partica LA-950V2. Total carbon content was determined in dried samples using a LECO TruSpec CN autoanalyzer. To calculate organic carbon (OC), carbonates were first removed with fuming HCl (37%). $CaCO_3$ content was then estimated as 8.33 times inorganic carbon, using the molecular mass ratio.

The concentrations of ^{210}Pb were determined by alpha-spectroscopy following *Sanchez-Cabeza et al.* [1998]. ^{137}Cs concentrations were measured by γ counting of dried, homogenized samples in calibrated geometries for $2–3 \cdot 10^5$ s on a high purity intrinsic germanium detector. Gamma measurements were also used to determine the ^{226}Ra concentrations via the gamma emissions of ^{214}Pb. ^{210}Pb-derived sediment accumulation rates were calculated based on a one-dimensional, steady state constant ^{210}Pb flux:constant sedimentation model [*Krishnaswamy et al.*, 1971], constrained by the ^{137}Cs concentration profiles [*Masqué et al.*, 2003].

Historical data of the Palamós harbor trawling fleet (total number of trawlers, total horse power, and total gross tonnage) were obtained from official bulletins and from a compilation of data from the archives of the Palamós' Fishermen Guild, partially published in *Alegret and Garrido* [2004]. Recent official data from the Palamós trawling fleet (1992–2011) were provided by the Spanish Ministry of Agriculture, Livestock, and Environment. Additionally, personal interviews were conducted with fishermen from the Palamós harbor during 2013–2014 in order to obtain an estimate of the real engine power currently installed in the trawling vessels.

3. Results and Discussion

3.1. Sediment Core Characteristics

The sediment core collected in 2011 was composed of clayey silt (~25% clay and ~75% silt) with <3% of sand at all depths. Water content in the sediment samples oscillated between 38 and 46% and dry bulk density increased consistently from ~0.4 g cm^{-3} at the topmost section to 0.8 g cm^{-3} at 15 cm depth, reaching ~0.9 g cm^{-3} at the bottom of the core. $CaCO_3$ contents were about 25% in the topmost 10 cm and showed slightly lower values (in the range 23–25%) in the deeper sections of the core, while OC displayed slightly lower concentrations (~0.70%) in the upper 10 cm than in deeper sections, where it ranged from 0.75 to 0.80% (data not shown).

The deepest layer in the core at which ^{137}Cs was detected was at 44 cm depth, providing the ~1954 time marker corresponding to the year when this artificial radionuclide was first introduced to the environment as a consequence of atmospheric nuclear bomb testing. Higher ^{137}Cs concentrations were observed above this region, with two relative maxima at 39 and 36 cm depth, corresponding to the historical peak fallout around 1963 (Figure 2a).

^{210}Pb concentration in the bottommost sample was 67 ± 4 Bq kg^{-1}, a value slightly higher than the typical supported levels (~25–35 Bq kg^{-1}) known for this region [*Sanchez-Cabeza et al.*, 1999; *Martín et al.*, 2008], and the concentration of its effective parent ^{226}Ra measured along the core (33.4 ± 4.0 Bq kg^{-1}). This indicates that the horizon of excess ^{210}Pb ($^{210}Pb_{xs}$), where total ^{210}Pb is in equilibrium with ^{226}Ra, was not reached. The $^{210}Pb_{xs}$ concentrations throughout the sediment core were then calculated by subtracting an average ^{226}Ra concentration from total ^{210}Pb concentrations.

From the core bottom to 37 cm depth, we identified a section with a gently sloping $^{210}Pb_{xs}$ profile (Figure 2a), indicating a steady state accumulation of sediment with a calculated sedimentation rate of 0.20 ± 0.02 g cm^{-2} yr^{-1} (0.25 ± 0.02 cm yr^{-1}; $R^2 = 0.88$). From 37 cm depth to the sediment water interface, the $^{210}Pb_{xs}$ profile suggests a non steady state accumulation of sediment, presumably generated by a series of depositional events, which complicates the reconstruction of the recent sedimentation history. However, the ^{137}Cs concentration profile allowed us to date the time of this change as the early 1970s. Therefore, integrating all the depositional events in this upper sedimentary unit during the last four decades, we obtained a mean sedimentation rate of ~0.78 g cm^{-2} yr^{-1} (~1.09 cm yr^{-1}) (Figure 2a).

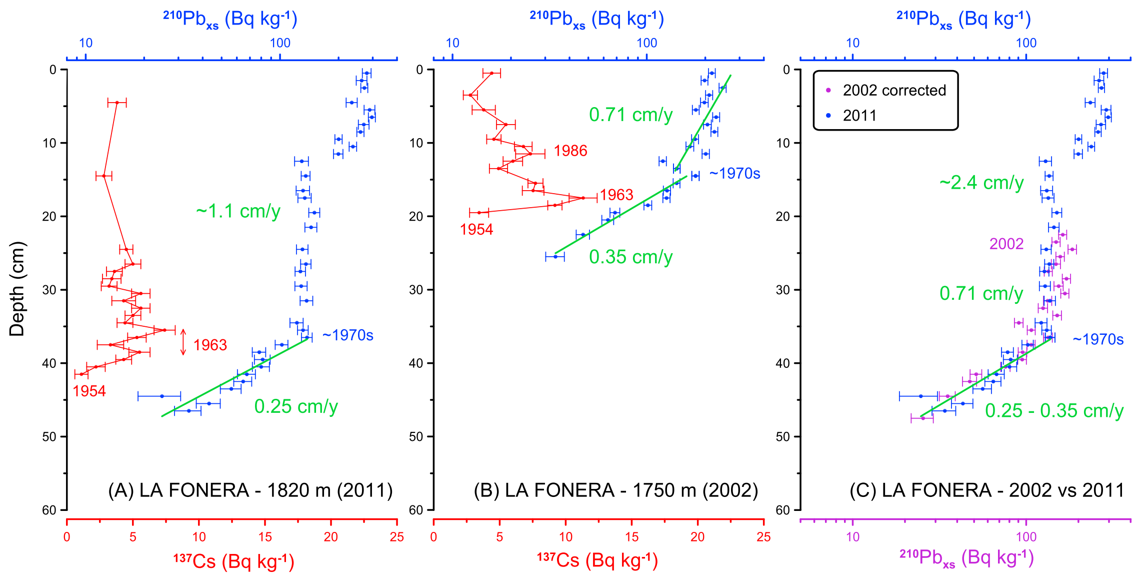

Figure 2. $^{210}Pb_{xs}$ and ^{137}Cs concentration profiles of sediment cores collected from the lower La Fonera (Palamós) canyon axis in (a) 2011 and (b) 2002. (c) A downward shift of 23 cm was applied in the 2002 core together with a radioactive decay correction of the $^{210}Pb_{xs}$ concentrations to compare both records. The years assigned to specific core depths and the sedimentation rates estimated for each sedimentary section are shown.

3.2. Comparison Between 2002 and 2011 Sedimentary Records

Figure 2b illustrates the ^{137}Cs and $^{210}Pb_{xs}$ profiles in the sediment core collected in 2002 at 1750 m depth within La Fonera canyon axis (see *Martín et al.* [2008] for details). ^{137}Cs was first detected at 20 cm depth, providing the ~1954 time horizon, whereas the 1963 fallout peak and the relative maximum attributable to the 1986 Chernobyl accident were found at 18 and 12 cm depth, respectively. Two different slopes in the $^{210}Pb_{xs}$ profile were observed. In the lower part of the core, up to 15 cm depth, a sedimentation rate of 0.23 ± 0.02 g cm^{-2} yr^{-1} (0.35 ± 0.03 cm yr^{-1}; $R^2 = 0.93$) was established, whereas the upper part of the core showed a rate of 0.42 ± 0.04 g cm^{-2} yr^{-1} (0.71 ± 0.06 cm yr^{-1}; $R^2 = 0.50$) (Figure 2b). As previously mentioned, the sedimentation model established this change during the 1970s.

To compare the sediment cores from both study years, we assumed that the regions where the slope of the $^{210}Pb_{xs}$ profiles change represent synchronous time horizons. Hence, in Figure 2c, the vertical axis of the core collected in 2002 was shifted 22 cm downward and the $^{210}Pb_{xs}$ concentrations were corrected by the radioactive decay of this radionuclide ($T_{1/2} = 22.3$ years), taking into account the 9 years that elapsed between coring operations. This displacement is coherent with the occurrence at consistent depth intervals of the ^{137}Cs maxima and the deepest appearance of detectable ^{137}Cs in both cores.

The comparison between cores is made more coherent by considering the ^{137}Cs inventories in the sedimentary units of similar ages. The ^{137}Cs inventory of 818 ± 28 Bq m^{-2} for the entire 2002 core would correspond to 675 ± 22 Bq m^{-2} measured for the sediment column below 22 cm in the 2011 core. The difference of 17.4% is consistent with a theoretical loss of 18.6% by radioactive decay of this radionuclide ($T_{1/2} = 30.2$ years) after 9 years. A similar inventory comparison for $^{210}Pb_{xs}$ is not straightforward because the supported level was not reached at the bottom of the core collected in 2011.

3.3. Linking Deep Sedimentation Within the Canyon With the Recent Evolution of the Palamós Trawling Fleet

The deep-sea shrimp *A.* antennatus has been fished using trawl gear in La Fonera Canyon for more than 60 years. However, fishing power was negligible until the mid-1960s [*Alegret and Garrido*, 2004], when the Palamós fleet underwent a major industrialization that accelerated in the 1970s, as revealed by the evolution of number of trawlers and the sum of their horsepower (Figure 3). The 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 the working depth and

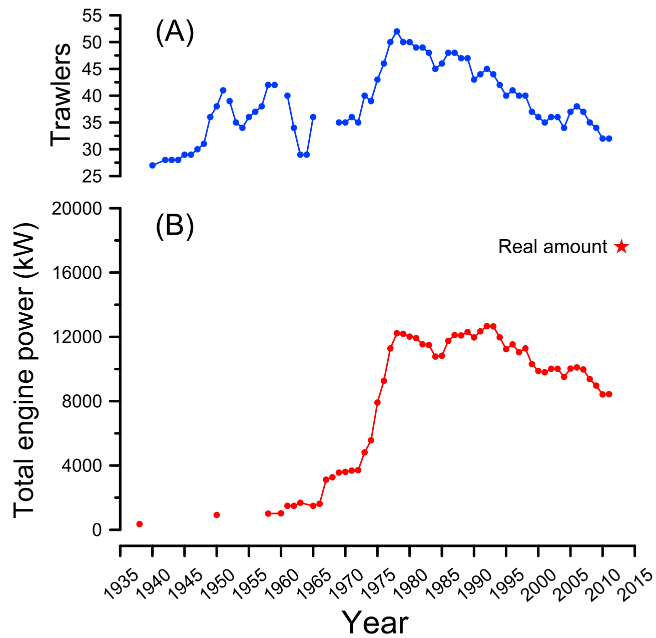

Figure 3. Historical evolution of total number of (a) trawlers and the official (b) total engine power of the Palamós trawling fleet. The red star represents the real amount of the total engine power currently installed, obtained through fishermen interviews.

haul duration, all of which are indicative of the capacity to resuspend bottom sediments [*Martín et al.*, 2104a]. The analysis of the $^{210}Pb_{xs}$ and ^{137}Cs concentration profiles in the two cores collected 9 years apart (Figure 2) supports the hypothesis that this fishing practice might have induced a substantial increase of sediment accumulation rates in the lower part of this submarine canyon since the 1970s. It is noteworthy that the closest major river to this submarine canyon (Ter River) was dammed along its lower course during 1962–1967—a common practice in most of the NW Mediterranean rivers at that time—and these dams are currently retaining more than 90% of its sediment load [*Liquete et al.*, 2009]. Accordingly, the sediment accumulation rates in this continental margin should have decreased, but our results show an increasing rate that could be attributable to trawling-induced erosion and remobilization of bottom sediments along the canyon flanks [*Martín et al.*, 2104b]. Indeed, approximately $1.0 \cdot 10^{-2}$ km^3 of sediment has been estimated to be remobilized from the northern canyon flank since the industrialization of the bottom trawling fleet [*Puig et al.*, 2012].

Based on the combined (and adjusted) $^{210}Pb_{xs}$ profiles of both cores, from 37 to 13 cm depth, the $^{210}Pb_{xs}$ concentrations showed similar values between 120 and 160 Bq kg^{-1}, and above this level concentrations ranged between 230 and 330 Bq kg^{-1} (Figure 2c). This recent sedimentary unit with higher $^{210}Pb_{xs}$ activity could be explained by the arrival of surface sediments resuspended from pristine slope regions that were not previously trawled, as untrawled sediments along the canyon flanks show comparable surface $^{210}Pb_{xs}$ concentrations [*Martín et al.*, 2104b]. This is consistent with the common practice to continuously explore deeper (and untrawled) fishing grounds over time.

Even though the pre-1970s sedimentation rate in this part of the submarine canyon axis has been estimated at 0.25–0.35 cm yr^{-1}, and the rate estimated for the post-1970s layer accounts for an average of 0.71 cm yr^{-1} in 2002 (Figure 2b) and ~1.1 cm yr^{-1} in 2011 (Figure 2a), the comparison of both cores suggests that an enhancement of sediment accumulation might have occurred in the lower reaches of this submarine canyon during the last decade. The approximately 22 cm of sediment that appears to have been accumulated in 9 years would represent a recent sedimentation rate of ~2.4 cm yr^{-1}, an order of magnitude higher than the pre-1970s values (Figure 2c).

This enhanced sedimentation rate during the last decade is seemingly inconsistent with the slight decrease in total power of the fishing fleet from the 1990s as obtained from the official databases (Figure 3). However, this decreasing trend actually reflects a slow reduction in the total number of trawlers (Figure 3a). Simultaneously, ship owners have been introducing technical improvements in the trawlers (namely, more powerful engines and bigger gear), a practice that leaves no trace in the official reports, since only the horsepower of newly built ships is incorporated in the fleet census [*Irazola et al.*, 1996; *Alegret and Garrido*, 2004]. Data from personal interviews compiled during 2013–2014 revealed a real total engine power of 16700 kW for the Palamós trawling fleet, a figure that doubles the amount reported in the official statistics (Figure 3b). Interviews also revealed that the most dramatic increases in the installed power were introduced at the beginning of the 21st century. Furthermore, the Palamós harbor has evolved toward an increasing economic dependence on, and specialization in, the *A. antennatus* fishery over the last decade

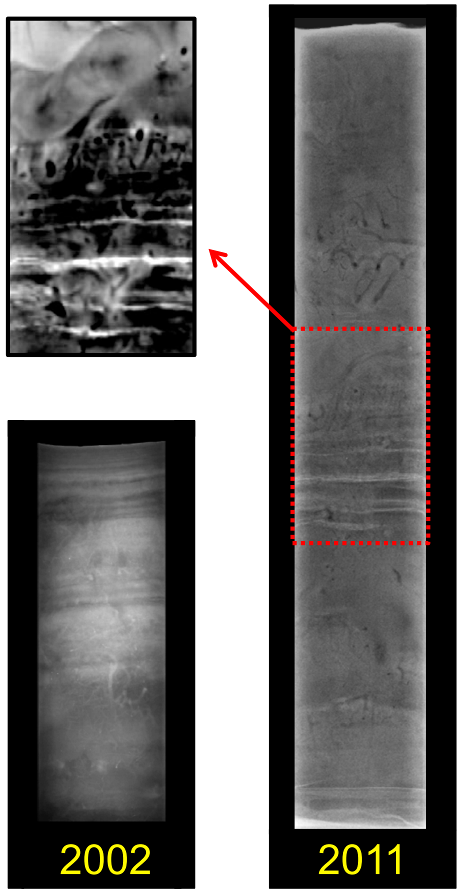

Figure 4. X-radiographs of sediment cores collected in 2002 and in 2011 with a detail of the vertical computerized tomography reconstruction. Note the concentric locomotion track (scolicia) above the preserved laminations attributed to the burrowing sea urchin *Brissopsis lyrifera*.

[*Alegret and Garrido*, 2008]. This may also explain the apparent increase of sediment accumulation at the lower canyon since 2002, as a result of progressive concentration of the fishing effort on to this deep-sea species.

The fact that just a single coring location has been analyzed in detail prevents an assessment of the total area of the canyon that could be affected by the trawling-induced enhanced deposition of sediments. Similar analysis in new sediment cores collected along the entire canyon axis will be necessary to fully support our interpretations and to determine the spatial distribution and thickness of this sedimentary depocenter.

3.4. Enhanced Bioturbation in Recent Times: A Response to the Formation of an Anthropogenic Depocenter

The X-radiograph from the upper part of the sediment core collected in 2002 showed a well-preserved subcentimetric sedimentary layering (Figure 4). This layering was interpreted as a succession of deposition pulses associated with the arrival of trawling-induced sediment gravity flows [*Martín et al.*, 2008]. The good preservation of these physical structures was explained as a temporary hampering of biological mixing, resulting from suffocation of bioturbating fauna. However, these physical structures have become partially blurred or replaced with biogenic fabric in the X-radiograph from the 2011 sediment core (Figure 4). Nevertheless, when the images of both cores are shifted 22 cm, the respective areas of most marked physical laminations are found at comparable depths. This suggests that bioturbation, if hampered at the time of collection of the 2002 sediment core, was subsequently reactivated.

Different ichnofabrics are observable in the 2011 X-radiograph, testifying to a diverse burrowing fauna, which was further documented by computed tomography. It is noteworthy that the upper limit of recognizable laminations is underlain—and apparently faded—by a peculiar track mark consisting in a series of crescent-shaped concentric laminations (see CT reconstruction in Figure 4). Such ichnofabrics are termed “scolicia” and are well represented in both the fossil record and present-day marine sediments [*Fu and Werner*, 2000], resulting from the burrowing activity of endobenthic echinoids [*Bromley and Asgaard*, 1975].

Remotely operated vehicle images collected along La Fonera deep canyon axis seafloor evidenced a large presence and densities of the burrowing sea urchin *Brissopsis lyrifera* [*Mecho et al.*, 2014]. This species is known to be a very active burrower capable of substantially reworking fine-grained marine sediments [*Widdicombe and Austen*, 1998; *Hollertz and Duchêne*, 2001] and, as such, is plausibly responsible for the scolicia and intense bioturbation observed in the upper layers of the 2011 sediment core. *Tecchio et al.* [2013] also found this species in high densities in the neighboring Blanes canyon axis, while it was absent from the adjacent open slope. This suggests that the canyon environment might be functioning as refuge area for this species, since according to claims by local fishermen, *B. lyrifera* was present in high numbers in the slope in previous decades. The colonization of the deep canyon axis by *B. lyrifera*, therefore, seems to be a side effect of the formation of this recent (post-2002) anthropogenic depocenter, which offers a suitable environment for their proliferation.

4. Summary

We have documented a significant increase in the net sediment accumulation rate in La Fonera (Palamós) lower canyon axis (1820 m depth) since the 1970s, coinciding with the industrialization of the local trawling fleet. This increase was documented to be of a factor of 2 until 2002, but the recent (post-2002) sedimentation rates indicate that the change could be one order of magnitude higher, reaching ~2.4 cm yr^{-1}. Currently, the lower canyon axis region appears to act as an anthropogenic depocenter of particles remobilized by trawling activities along the canyon flanks. However, the analysis of a single location does not allow the area of canyon affected by this enhanced deposition to be determined. An associated observation is the appearance of the burrowing echinoid *Brissopsis lyrifera*, which seems to have colonized the lower canyon axis, following the formation of this new, deep anthropogenic deposit of fine-grained material. Further sediment core sampling and dating should be conducted along the entire axis of La Fonera Canyon, as well as in other submarine canyons whose flanks are impacted by bottom trawling activities, to provide a wider regional (or global) view of this phenomenon.

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References

Alegret, J. L., and A. Garrido (2004), *Historia de la Confraria de Pescadors de Palamós*, 295 pp., Confraria de Pescadors de Palamós, Girona.

Alegret, J. L., and A. Garrido (2008), History of the Palamós Harbor: Development, associationism and migration, AREAS, *Rev. Int. Cienc. Soc.*, *27*, 27–40.

Bromley, R. G., and U. Asgaard (1975), Sediment structures produced by a spatangoid echinoid: A problem of preservation, *Bull. Geol. Soc. Den.*, *24*(3–4), 261–281.

Canals, M., J. B. Company, D. Martín, A. Sànchez-Vidal, and E. Ramirez-Llodrà (2013), Integrated study of Mediterranean deep canyons: Novel results and future challenges, *Prog. Oceanogr.*, *118*, 1–27, doi:10.1016/j.pocean.2013.09.004.

Fu, S., and F. Werner (2000), Distribution, ecology and taphonomy of the organism trace, Scolicia, in northeast Atlantic deep-sea sediments, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *156*(3–4), 289–300, doi:10.1016/s0031-0182(99)00146-7.

Hollertz, K., and J. C. Duchêne (2001), Burrowing behavior and sediment reworking in the heart urchin Brissopsis lyrifera Forbes (Spatangoida), *Mar. Biol.*, *139*(5), 951–957, doi:10.1007/s002270100629.

Irazola, M., A. Lucchetti, J. Lleonart, A. Ocaña, J. M. Tapia, and S. Tudela (1996), *La Pesca en el Siglo Xxi, Propuestas Para Una Gestión Pesquera Racional en Cataluña*, 289 pp., CCOO-CEPROM, Barcelona.

Jones, J. B. (1992), Environmental impact of trawling on the seabed: A review, *N. Z. J. Mar. Freshwater Res.*, *26*, 59–67.

Krishnaswamy, S., D. Lal, J. Martin, and M. Meybeck (1971), Geochronology of lake sediments, *Earth Planet. Sci. Lett.*, *11*, 407–414.

Liquete, C., M. Canals, W. Ludwig, and P. Arnau (2009), Sediment discharge of the rivers of Catalonia, NE Spain, and the influence of human impacts, *J. Hydrol.*, *366*(1–4), 76–88, doi:10.1016/j.jhydrol.2008.12.013.

Lopez-Fernandez, P., A. Calafat, A. Sanchez-Vidal, M. Canals, M. M. Flexas, J. Cateura, and J. B. Company (2013), Multiple drivers of particle fluxes in the Blanes submarine canyon and southern open slope: Results of a year round experiment, *Prog. Oceanogr.*, *118*, 95–107, doi:10.1016/j.pocean.2013.07.029.

Martín, J., P. Puig, A. Palanques, P. Masqué, and J. García-Orellana (2008), Effect of commercial trawling on the deep sedimentation in a Mediterranean submarine canyon, *Mar. Geol.*, *252*(3–4), 150–155, doi:10.1016/j.margeo.2008.03.012.

Martín, J., P. Puig, A. Palanques, and M. Ribó (2014), Trawling-induced daily sediment resuspension in the flank of a Mediterranean submarine canyon, *Deep Sea Res., Part II*, *104*, 174–183, doi:10.1016/j.dsr2.2013.05.036.

Martín, J., P. Puig, A. Palanques, and A. Giamportone (2104a), Commercial bottom trawling as a driver of sediment dynamics and deep seascape evolution in the Anthropocene, *Anthropocene*, *7*, 1–15, doi:10.1016/j.ancene.2015.01.002.

Martín, J., P. Puig, P. Masqué, A. Palanques, and A. Sánchez-Gómez (2104b), Impact of bottom trawling on deep-sea sediment properties along the flanks of a submarine canyon, *PLoS One*, *9*(8), e104536, doi:10.1371/journal.pone.0104536.

Masqué, P., J. Fabres, M. Canals, J. A. Sanchez-Cabeza, A. Sanchez-Vidal, I. Cacho, A. M. Calafat, and J. M. Bruach (2003), Accumulation rates of major constituents of hemipelagic sediments in the deep Alboran Sea: A centennial perspective of sedimentary dynamics, *Mar. Geol.*, *193*(3–4), 207–233, doi:10.1016/S0025-3227(02)00593-5.

Mecho, A., D. S. M. Billett, E. Ramírez-Llodra, J. Aguzzi, P. A. Tyler, and J. B. Company (2014), First records, rediscovery and compilation of deep-sea echinoderms in the middle and lower continental slope of the Mediterranean Sea, *Sci. Mar.*, *78*(2), 281–302, doi:10.3989/scimar.03983.30C.

Nittrouer, C. A., and L. D. Wright (1994), Transport of particles across continental shelves, *Rev. Geophys.*, *32*(1), 85–113, doi:10.1029/93RG02603.

Palanques, A., J. Martín, P. Puig, J. Guillén, J. B. Company, and F. Sardà (2006), Evidence of sediment gravity flows induced by trawling in the Palamós (Fonera) submarine canyon (northwestern Mediterranean), *Deep Sea Res., Part I*, *53*(2), 201–214, doi:10.1016/j.dsr.2005.10.003.

Puig, P., and A. Palanques (1998), Temporal variability and composition of settling particle fluxes on the Barcelona continental margin (Northwestern Mediterranean), *J. Mar. Res.*, *56*(3), 639–654, doi:10.1357/002224098765213612.

Puig, P., M. Canals, J. B. Company, J. Martín, D. Amblàs, G. Lastras, A. Palanques, and A. M. Calafat (2012), Ploughing the deep seafloor, *Nature*, *489*(7415), 286–289, doi:10.1038/nature11410.

Sanchez-Cabeza, J. A., P. Masqué, and I. Ani-Ragolta (1998), ^{210}Pb and ^{210}Po analysis in sediments and soils by microwave acid digestion, *J. Radioanal. Nucl. Chem.*, *227*(1–2), 19–22, doi:10.1007/BF02386425.

Sanchez-Cabeza, J. A., P. Masqué, I. Ani-Ragolta, J. Merino, M. Frignani, F. Alvisi, A. Palanques, and P. Puig (1999), Sediment accumulation rates in the southern Barcelona margin (NW Mediterranean Sea) derived from ^{210}Pb and ^{137}Cs chronology, *Prog. Oceanogr.*, *44*(1–3), 313–332, doi:10.1016/S0079-6611(99)00031-2.

Syvitski, J. P. M., C. J. Vörösmarty, A. J. Kettner, and P. Green (2005), Impact of humans on the flux of terrestrial sediment to the global coastal ocean, *Science*, *308*(5720), 376–380, doi:10.1126/science.1109454.

Tecchio, S., E. Ramírez-Llodra, A. Sanchez-Vidal, J. Aguzzi, M. M. Flexas, F. Sardà, and J. B. Company (2013), Seasonal fluctuations of deep megabenthos: Finding evidence of standing stock accumulation in a flux-rich continental slope, *Prog. Oceanogr.*, *118*, 188–198, doi:10.1016/j.pocean.2013.07.015.

Walsh, J. P., and C. A. Nittrouer (2009), Understanding fine-grained river-sediment dispersal on continental margins, *Mar. Geol.*, *263*(1–4), 34–45, doi:10.1016/j.margeo.2009.03.016.

Widdicombe, S., and M. C. Austen (1998), Experimental evidence for the role of Brissopsis lyrifera (Forbes, 1841) as a critical species in the maintenance of benthic diversity and the modification of sediment chemistry, *J. Exp. Mar. Biol. Ecol.*, *228*(2), 241–255, doi:10.1016/S0022-0981(98)00032-X.