Implications of trawling-induced resuspension events in the generation of nepheloid layers in the Foix submarine canyon (NW Mediterranean)

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Abstract

The temporal evolution of water column turbidity was studied on a submarine canyon on the Barcelona continental margin. From April to June 2014, an instrumented mooring array equipped with an autonomous hydrographic profiler with a CTD and a turbidimeter was deployed in the Foix canyon axis at 870 m depth. The instruments were programmed to collect hydrographic profiles once per day to provide a view of the temporal evolution of water column characteristics from 200 to 800 m water depth. The results illustrate a well-defined water turbidity structure of particulate matter distributed in intermediate nepheloid layers (INLs) developed between 300 and 500 m water depth and above the canyon rims, and INLs and near-bottom nepheloid layers (BNLs) confined inside the canyon between 650 and 800 m water depth. Data from fishing vessels activity at the time of the deployment was obtained from Vessel Monitoring System (VMS). The presence and location of the fishing vessels in the study area suggested a relationship between trawling activity and the generation of such layers. Nepheloid layers were absent during the first part of the deployment, when there was no fishing activity within the Foix Canyon axis or at the adjacent continental slope. Later, with the beginning of trawling activity on the fishing grounds close to the canyon, both INLs and BNLs were observed in the profiling casts, suggesting a causative relationship with fishing activities.

27 Additionally, the hydrodynamic conditions within the canyon also seem to favour particle
28 retention and to increase water turbidity in thick BNLs when water circulation is directed
29 up-canyon. Bottom trawling appears to act as a main sediment resuspension mechanism
30 in the Barcelona continental slope regions, increasing suspended sediment
31 concentration at specific water depths where fishing grounds are located. Suspended
32 particles are then advected and propagate along and across-margin by ambient currents
33 via nepheloid layers.

34 **Keywords:**

35 Submarine canyon (RT)

36 Sediment transport (RT)

37 Nepheloid structure

38 Bottom trawling (RT)

39 Resuspension (RT)

40 Northwestern Mediterranean

41
42 **1. Introduction**

43 The transport of matter and energy from the upper ocean to the seafloor is especially
44 important in continental margins due to the large material inputs from both terrestrial
45 sources and high productivity coastal waters (Walsh, 1991). Particulate matter is often
46 introduced into the ocean by biological production, riverine and aeolian supplies or
47 glaciers (Gardner et al., 1990; Gardner and Walsh, 1990). Once in the water column, the
48 distribution of suspended particulate matter strongly depends on the regional and
49 physical conditions, as well as the hydrographic structure and the hydrodynamic
50 processes. Particularly, physical gradients, such as thermoclines or density fronts, and
51 geostrophic currents are some of the most common factors controlling particulate matter

distribution and exchanges in the water column (Palanques and Biscaye, 1992; Spurgin and Allen, 2014). Additionally, topographic structures, such as submarine canyons incising continental margins, can promote complex hydrographic and sedimentary conditions that also favour the transport of material from the continental shelves to deeper environments (Gardner, 1989; Puig et al., 2001; Canals et al., 2013; Puig et al., 2014; Wilson et al., 2015a).

Nepheloid layers (i.e., cloudy layers within the water column with high concentrations of suspended particulate material compared with the surrounding clear waters) are considered as the diluted product of sediment transport processes and are significant contributors to the shelf-slope exchanges of material (McCave, 1986; Amin and Huthnance, 1999; Wilson et al., 2015). They are formed by a balance of settling and resuspension processes and are considered as important lateral transporters of sediments and organic matter (Amin and Huthnance, 1999; Wilson, 2016). These turbid layers can regularly be observed at the upper ocean, where they form surface nepheloid layers (SNLs), and very often near the seabed, forming bottom or benthic nepheloid layers (BNLs). Additionally, they can be detected along isopycnals at different water depths as intermediate nepheloid layers (INLs) (Dickson and McCave, 1986; McCave, 1986; Puig et al., 2004; Karageorgis et al., 2017).

In deep-sea environments (>200 m water depth), the energy associated with internal waves has been hypothesized as the main mechanism that initiates periodic sediment resuspension on continental margins and slopes as well as within submarine canyons (Cacchione and Drake, 1986). Bottom shear stress caused by internal waves can be large enough to resuspend sediment over these areas, and lead to the formation of localised intermediate and bottom nepheloid layers at certain depths (McCave, 1986; Cacchione and Drake, 1986; Gardner, 1989; Puig et al., 2004). However, bottom fishing activities can resuspend as well surface sediments and contribute to the transport of suspended particles (e.g. Durrieu de Madron, 2005; Martín et al., 2014a; Palanques et

al., 2014; Linders et al., 2017), since the trawling gear produces relative high bed shear stress and high turbulence when it interacts with the seabed (O'Neill and Summerbell, 2011). As such, in certain continental margins, deep-sea trawling has been recognised as an important source of suspended material over slope regions (e.g. Chronis et al., 2000; Puig et al., 2012; Wilson et al., 2015b; Daly et al., 2017), being able to overcome natural processes as the main mechanism of sediment resuspension.

On the Barcelona continental margin (NW Mediterranean), Puig and Palanques (1998a) described the general pattern of water column suspended particles distribution. This study revealed that particulate matter was consistently distributed in surface, intermediate and near-bottom nepheloid layers that were related to topographic and hydrographic structures. These authors suggested natural processes (i.e., internal waves' activity focussed along the permanent shelf-slope density front) as the main mechanisms that could contribute to form and maintain these nepheloid layers. Nonetheless, in the NW Mediterranean margin, deep-sea trawling activities have been identified as an important mechanism causing resuspension and erosion of sediments from fishing grounds (Puig et al., 2012; Martín et al., 2014b; Pusceddu et al., 2014). This mechanism has caused increased sediment accumulation rates within several submarine canyon axes of this margin since the 1960-70s, as a result of the expansion and industrialization of the trawling fleets at that time (Martín et al., 2008; Puig et al., 2015; Paradis et al., 2017). In the Foix submarine canyon (Fig. 1), Paradis et al. (2018) reported recent sediment accumulation rates from a core collected in 2013 at the canyon axis at 860 m depth, and compared them with a sediment core retrieved in 1993 at the same location (Sanchez-Cabeza et al., 1999). At this site, it was recorded an almost two-fold increase in the sedimentation rates in the 1960-70s, from 0.5 cm/y to 0.9 cm/y, and a further increase (up to 1.8 cm/y) in the early 2000s, after a new renewal of the trawling fleet (Paradis et al., 2018).

In the present paper, we aim to assess the role of trawling fisheries in resuspending bottom sediments within the Foix Canyon and discuss the implications of trawled-induced resuspension events in the generation of nepheloid layers in the NW Mediterranean margin. With this purpose in mind, from April to June 2014, a mooring array equipped with an autonomous hydrographic profiler was deployed at the Foix Canyon axis at a water depth of 870 m, a slightly deeper location than the maximum working depth of the local trawling fleet. Vessel Monitoring System (VMS) was used in order to assess the position of fishing vessels at the time of the instrumented mooring deployment.

2. Materials and methods

2.1. Study area

The Foix Canyon system is located in the Catalan margin a few kilometres south of Barcelona (Fig. 1). This canyon incises the shelf-break at 90 m depth and moulds the seafloor down to its confluence with the Valencia channel at a water depth of 2180 m (Canals et al., 2013; Tubau et al., 2013). It consists of two sinuous branches, the eastern Foix and the western Foix branches, that conjoin at 1340 m water depth (Tubau et al., 2013). The canyon cross section at its eastern branch is V-shaped along the first 3.7 km and is defined by an axial incision, while the western branch is U-shaped, characterised by the presence of small tributaries and sedimentary instabilities (Alonso et al., 1984; Tubau et al., 2013). On the upper slope, its steep walls can reach heights of 400 m and maximum gradients of 23° at the mid canyon (Alonso et al., 1984). It also becomes narrow with depth, decreasing from 4 km at the shelf-break to 2 km at a depth of 1200 m (Fig. 1).

This canyon intercepts particulate matter from the continent and acts as a preferential conduit for such sediments to the slope during sporadic events such as storms or river

discharges (Puig and Palanques, 1998b). It is influenced by the geostrophic circulation of the Liguro-Provençal-Catalan current (NW Mediterranean), that flows towards the southwest and along the continental slope (Millot, 1987; Font et al., 1988).

Current speed fluctuations along this canyon are mainly controlled by the local inertial motion and by low-frequency oscillations (from 6 to 10 days) linked to meteorological forcing conditions (Puig et al., 2000). Near-bottom currents recorded inside the canyon are highly constrained by the canyon topography, and are mainly oriented along the canyon axis both in the up- and down-canyon directions, although at the canyon head currents do not display such a clear trend of up- and down-canyon alternations. In intermediate waters at the slope depths, currents are mainly oriented along the margin towards the southwest, according to the main flow direction of the geostrophic circulation (Puig et al., 2000).

The fisheries that at present are economically more important on the Catalan continental margin take place on slope fishing grounds and are targeting the Norway lobster *Nephrops norvegicus* at depths ~300-500 m, and the blue and red deep-sea shrimp *Aristeus antennatus*, at depths ~600-900 m (Sardà et al., 1994; Lleonart, 1990; Maynou et al., 1998). The spatial distribution of these two main fishing grounds in some areas can be easily recognized in the bottom trawling footprint of Figure 1. The Foix Canyon and its surrounding waters are mainly frequented by trawling vessels from Vilanova i la Geltrú and Barcelona harbours (Fig. 1). The local fleets on the study area operate on a daily basis during weekdays, from 7 a.m. to 4 p.m., remaining at the harbours on weekends, holidays and local festivities.

2.3. Time-series observations

From April to June 2014, a total of 58 hydrographic profiles were obtained by an instrumented mooring array equipped with an autonomous hydrographic profiler (Aqualog) deployed in the Foix canyon axis (41° 05.55820' N; 001° 55.58104' E) at 870

m depth (Fig.1; Fig. 2). The Aqualog moves up and down along a fixed vertical line at a fixed position at programmed frequencies, collecting regular profiles over a large depth range at high temporal and vertical resolutions (Otrovskii et al., 2013; Kershaw, 2015; Solé et al., 2016). In this deployment, the Aqualog profiler was programmed to perform one up- and down-cast per day at 12 a.m., profiling from 800 m to 200 m, and back to 800 m (parking depth), at a relative speed of 25 cm/s. Every up- and down-cast took approximately one hour to be completed. The profiler was equipped with a SeaBird 19 plus v2 CTD probe configured to measure temperature, salinity and pressure at 1 second intervals. Temperature and salinity were used to characterize the hydrographic structure of the study site. The profiler was also equipped with a SeaPoint turbidity sensor, programmed to measure turbidity, expressed in mV, at 1 second intervals. The sensor gain was set at 0-5 V, and a range of 0-25 FTU. The readings were transformed into Formazin Turbidity Units (FTU), and since water samples were not taken for calibration, reported values were converted to estimates of suspended sediment concentration (SSC) in mg/L using the general calibration of Guillén et al. (2000) for the Western Mediterranean. Estimates of SSC values were reported above a background concentration corresponding to the clear water minimum of each profile.

To proceed with a homogenous methodology for all parameters, all the data was interpolated to 1 m vertical resolution, obtaining a matrix for the whole sampling period composed of 58 down-casts. The measured and calculated parameters were represented using Ocean Data View (ODV) software (Schlitzer, 2010).

According to the bathymetric section in Figure 2 and the Aqualog profiling range, and based on the position of the canyon rims and the position of trawlers throughout the monitoring period, data was described and analysed considering two depth ranges: 1) canyon-unconfined waters (depths between 200 and 500 m) and 2) canyon-confined waters (depths greater than 500 m).

2.4. Computation of the net particulate standing crop

A depth-average vertical integration of SSC was computed to calculate the net particulate standing crop on each down-cast (Fig. 3). This parameter was calculated for the concentration excess over the value of the clear water minimum on each cast and integrated over the height of the profiling range following:

$$\text{Net particulate standing crop} = \frac{1}{h} \int_0^h \text{SSC}(z) dz$$

where h is the depth of the considered water column and $\text{SSC}(z)$ represents the estimated SSC values, in mg/L (Karageorgis and Anagnostou, 2003).

The net particulate standing crop provides an estimation of the input of particles introduced in the water column from bottom resuspension. This estimation differs from the original methodology used by Biscaye and Eittreim (1977), as these authors defined this parameter in oceanic waters for BNLs, as the suspended matter which is found below the clear water minimum. Here, we also took into account the contribution of INLs at various levels in the water column (Fig. 3).

2.5. Fishing fleet data

The activity of the fishing vessels operating in the Foix Canyon fishing grounds near the mooring location was obtained from the Fishing Monitoring Centre of the Spanish General Secretariat of Maritime Fishing (SEGEMAR) through Vessel Monitoring System (VMS). Vessels with VMS provide their position using Global Positioning System (GPS) and transmit this information in approximately 10 minutes at intervals of 2 hours or less. This system also gives vessels' direction and speed, which is also useful to determine whether they are sailing, fishing or drifting.

However, VMS data for research and impact assessment has some limitations, including incomplete coverage of vessel activities, long durations between position records, and a lack of information on whether a vessel is actually fishing when the position is recorded.

Hence, it is necessary to make assumptions and interpretations when using VMS data as the principal source of information on fishing activities (Lambert et al., 2012).

The recorded VMS for the period from April 6 to June 2 included vessels' position, heading and speed measurements, port of origin and ID code. The total records for this period were reduced to those fitting the criteria for trawling activity. VMS data were filtered by speed (< 5 knots), allowing the identification of the vessels while fishing and not while navigating towards the harbour or other fishing grounds. Additionally, VMS data points were also filtered by working depth (> 200 m) to match the Aqualog profiling range. The total number of hauls were also considered, as they are an indicator of the times that a trawler tows an area and, hence, of trawlers' capacity to resuspend bottom sediments (Ragnarsson and Steingrímsson, 2003; Martín et al., 2014a). Finally, fishing vessels position at the study site was represented and plotted using ArcGis© v. 10.3.

3. Results

3.1. Hydrographic structure

Compiled data of all CTD casts revealed the presence of the three water masses permanently found in the NW Mediterranean basin, clearly distinguished by their characteristic potential temperature and salinity profiles (Fig. 4).

The shallowest waters (200-350 m water depth) were occupied by relatively warm (13.6 - 13.7 °C) and low salinity (38.0 - 38.2 psu) old Atlantic Waters (oAW) (Fig. 4, Fig. 5a, b). Below (350-600 m water depth), the θ -S diagram showed the more saline Levantine Intermediate Waters (LIW), characterized by both temperature and salinity relative maxima of 13.75 °C, and 38.55 psu, respectively (Fig. 4, Fig. 5a, b). The deepest waters (600-800 m water depth) were occupied by Western Mediterranean Deep Waters (WMDW) that exhibited temperature relative minima of 13.0 °C and salinity values between 38.4 and 38.55 psu (Fig. 4, Fig. 5a, b). The seasonal Western Intermediate

Water (WIW), occasionally found between the oAW and the LIW, was absent in the profiles (see <https://www.ciesm.org/catalog/WaterMassAcronyms.pdf> for more details).

Overall, temperature and salinity showed fluctuations of a hundred meters in depth throughout the 58 days of sampling, displaying a periodicity of 4-10 days (Fig. 5a, b). Several up-canyon water intrusions were also observed. The most relevant was detected from April 29 to May 3, when a cold (13 °C) and relatively less salty (38.5 psu) pool of WMDW occupied the lowest part of the profiled water column.

3.2. Suspended particulate matter distribution

Figure 6 shows the temporal variability in the distribution of the suspended sediment concentration (SSC) during the deployment. From April 6 to April 17, the vertical particulate matter distribution was quite homogenous and no SSC increases were observed in the profiled water column. From April 17, several increases of SSC (up to 1 mg/L) were recorded at intermediate water depths (300-500 m), mainly centred at ~400 m. These increases corresponded to ~150 m-thick INLs developed at depths of canyon-unconfined waters (Fig. 2). Deeper INLs were recorded sporadically within the canyon confined waters at ~700 m water depth, being thinner (60-90 m) than the shallower ones and reaching estimated SSC up to 1.2 mg/L, as in the case of the profiles on April 27 (cast #22) or April 30 (cast #25).

On May 1, the occurrence of a relative high turbidity event was observed particularly at the lowest part of cast #26, which most probably continued below the profiling range, down to the seafloor, generating a ~150 m thick BNL. This layer displayed the highest concentrations for the whole sampling period, reaching estimated SSC of 3.8 mg/L at 77 m above the bottom (Fig. 6).

Afterwards, several INLs were detected through the second half of the recording period, mainly in the profiling range corresponding to canyon-unconfined waters (Fig. 6). These INLs were found at the same depth ranges (300-500 m) as observed in the first half of

the sampling period, showing similar thickness, although during this part of the deployment they displayed higher estimates of SSC (1.1-1.6 mg/L). The distribution of the suspended particulate matter depicted the presence of a turbid water mass at intermediate depths that remained in the water column at least until the end of the experiment.

Within the canyon confined waters, no more significant near-BNLs were detected by the end of the experiment, but an INL was clearly noticeable at ~700 m water depth on May 31 (Fig. 6, cast #56). This deep INL was similar to one detected previously at the same depth range on April 27 (Fig. 6, cast #22). However, it was narrower (50 m thick) and had a maximum estimated SSC of 1.9 m/L (Fig. 6).

3.3. Trawling activity

During the experiment, VMS data showed that the fishing grounds around the Foix Canyon were exploited by 22 trawlers, mostly from Barcelona and Vilanova i la Geltrú harbours (Fig. 1). After speed and depth were filtered, vessels positions recorded by VMS appeared to follow the bathymetric contours and most of the trawling activity took place at 200-500 m water depth outside the canyon, along the fishing ground named *Can Pere Negre*, and at 600-800 m water depth inside the canyon, following the axis, along the fishing ground known as *Sant Salvador* (Fig. 1, Fig. 7, Lleonart, 1990).

The position of fishing vessels operating near the mooring site was plotted in detail, in six consecutive periods, each of them spanning 10 days of VMS data points except for the last one that lasted 6 days (Fig. 7). Table 1 summarizes the main characteristics of each period in terms of number of hauls and number of trawlers for the identified fishing grounds. Few isolated trawlers were observed to be fishing on the slope at depths >600 m (Fig. 7), but since they were far from the mooring location, they have not been taken into account in this analysis.

Time-series observations on VMS data revealed nearly no trawling activity around the mooring site during the first period (Fig. 7a). Only 10 hauls were counted, corresponding to five active vessels that were working at the slope fishing ground (Table 1). No fishing activity was detected at the axis fishing ground (Table 1; Fig. 7a).

The remaining periods (Fig. 7b-7f) were characterized by the presence of trawlers both at the axis and at the slope fishing grounds. During the second period, VMS data points were mostly clustered between the 200 m and the 500 m isobaths, suggesting that the majority of trawlers were working at the slope fishing ground (Table 1; Fig. 7b). Trawling activity throughout the third period remained similar to the previous period, although trawlers were concentrated at both the axis and the slope fishing grounds, but none of them were detected at depths greater than 400 m outside the canyon confinement (Fig. 7c). The number of trawlers and hauls was the same for both fishing grounds during this period (Table 1).

As far it concerns the last three periods, these were characterized by a relatively higher number of trawlers and hauls at both fishing grounds (Fig. 7d -7f; Table 1). The majority of trawling activity was detected along the axis and the slope fishing ground between the 200-500 m isobaths. Particularly, recordings for this second half of the survey showed that the highest number of hauls for both fishing grounds occurred during the fourth period (Fig. 7d; Table 1).

3.4. Relationship between net particulate standing crop and number of hauls

The number of hauls identified from the activity of trawlers operating nearby the Foix Canyon (Table 1) was used to infer trawlers' capacity to resuspend bottom sediments. Figure 8 illustrates the relation between the net particulate standing crop for each hydrographic cast and the number of hauls identified from the activity of trawlers operating at around the Foix Canyon fishing grounds on the previous day. Two approaches were considered, first the net particulate standing crop values of the entire

hydrographic profiles (200-800 m depth) were plotted against the total number of hauls on the slope and within the canyon (Fig. 8a), and second, the net particulate standing crop of the profiled section outside the canyon confinement (200-500 m depth) was plotted against the hauls of the slope fishing ground (Fig. 8b).

Despite the small number of hydrographic profiles obtained during fishing days, due to the exclusion of data during weekends and holidays, the overall fit of the two variables is fairly good. The correlation coefficients for the regression models are noticeably small, but according to the *p-values* ($p < 0.05$), both relations are statistically significant. The *r value* for the relation between the net particulate standing crop at intermediate waters and the number of hauls at the slope (Fig. 8b), where the major fishing activity took place (Fig. 7; Table 1), is slightly bigger than for the relation between the computed standing crop for the entire profiled depth range and the total number of hauls (Fig. 8a).

4. Discussion

4.1. Evidence of trawling-induced nepheloid layers using VMS data

The nepheloid structure of the Barcelona continental margin was determined by Puig and Palanques (1998a) using data from three hydrographic surveys conducted in 1992-93. These results showed that suspended particulate matter was mainly distributed at surface, intermediate and near-bottom nepheloid layers, and that nepheloid layer detachments were related to hydrographic structures. The maximum suspended sediment concentrations observed in the area occurred at the Foix submarine canyon, more specifically, at intermediate depths (between 300 and 500 m) associated with a suggested permanent INL. This layer was also observed at the adjacent continental slope (Puig and Palanques, 1998a). According to these authors, this slope INL was controlled by the shelf-slope density front and by the Liguro-Provençal-Catalan current, and was probably re-fed by sediment particles from other submarine canyons incising

the margin. Some authors (Caccione and Drake, 1986; Gardner, 1989) explained that shoaling and breaking of internal waves could lead to the formation and maintenance of INLs and near-BNLs over certain slopes and continental shelves. Therefore, in the Foix submarine canyon it was also suggested that breaking of near-inertial internal waves at the upper slope could resuspend bottom sediments where the foot of the density front intersects with the seabed and, thus, feeding this slope INL (Puig and Palanques, 1998a).

During the present study, several particulate matter detachments were found at intermediate depths within the unconfined canyon waters, mainly centred at 400 m over the slope region (Fig. 6). Even though the mechanism proposed by the latter authors involving internal waves' activity could be plausible, these slope INLs were not permanent and were just observed at specific time-spans throughout the sampling period (Fig. 6). The results presented in this study, when combined with data from fishing vessels positioning, suggest that trawling activity is likely responsible for most of the sediment resuspension that ultimately generates these INLs.

Analyses on VMS data revealed that all the observed nepheloid layers were detected during or after a period of trawling activity along the neighbouring fishing grounds of the Foix Canyon. When no particulate matter detachments were observed at the mooring location, particularly at the beginning of the monitoring period (Fig. 6), there was a low trawling activity at the neighbouring fishing grounds of the Foix Canyon (Fig. 7a). As an example, on April 11 there were no trawlers fishing near the mooring, neither at the slope nor at the axis fishing ground. At that time, the lowest suspended sediment concentration of the entire record was observed and VMS data identified a single trawler fishing at the 200 m depth isobath, far from the mooring location at shallower depths than the Aqualog profiling range (Fig. 9a). During the first 10-day period of monitoring (Fig. 7a), fishing activity was only detected on the slope fishing ground by 5 trawlers working at around the 400 m isobath (Table 1). This low trawling activity seems to be insufficient to induce

any particulate matter detachments that could be subsequently detected by the Aqualog at the mooring site (Fig. 1; Fig. 7; Fig. 9a).

Throughout the monitoring period, the presence of a higher number of trawlers on the slope fishing ground coincided with the INLs centred at 400 m water depth observed in the hydrographic profiles (Fig. 6). For instance, the position of trawlers on May 8 coincided temporally and spatially with the observed INL on May 9 (Fig. 6; Fig. 9b). Other hydrographic profiles, corresponding to the same monitoring period (Fig. 6; Fig. 7d), showed similar SSC levels related to the presence of trawlers operating on the slope fishing ground (Fig. 6). In fact, higher net particulate standing crops at this depth range (200-500 m) responded to a major number of hauls at the same bathymetric range, hence, to a higher trawling activity at the slope fishing ground (Fig. 8b). Therefore, it seems plausible that all observed particulate matter detachments at these depths were generated by the same mechanism. Once resuspension is generated by trawling, the presence of the geostrophic current flowing towards the southwest (Fig. 1) could have favoured particle transport from the slope, where fishing vessels were located (Fig. 7d), towards the canyon-unconfined waters over the mooring array (Fig. 2). Therefore, the Aqualog could have detected these increases in SSC as particulate matter was being detached from the slope over the canyon rims. The positive relationship between the quantification of the net particulate standing crop of the profiled section outside the canyon confinement and the number of hauls on the slope fishing ground supports this hypothesis (Fig. 8b). Nevertheless, previous hydrographic transects conducted along the axis of this canyon suggest that these INLs could have also been detached from the canyon head region (see Fig. 11 in Puig and Palanques, 1998a), from resuspension of trawlers operating along the canyon axis. Therefore, due to the presence of trawlers working simultaneously at both fishing grounds (Fig. 7d; Table 1), it is difficult to determine where these INLs were exactly generated, and probably both sources of

resuspended particles contributed to the observed INL detachments around 400 m water depth.

Within the canyon confinement, several deep INLs were also observed at ~700 m throughout the sampling period (Fig. 6). These confined INLs were recorded sporadically and displayed higher concentrations (~2 mg/L) than the slope unconfined INLs (Fig. 6). As an example, Figure 9c illustrates the confined INL observed on May 31 at the time that two trawlers were operating at the axis fishing ground. The development of these deep INLs is likely related to the presence of trawlers working along the main axis fishing ground, which can reach greater depths than the hauls on the adjacent slope. In this case, the natural conduit of the canyon and the alternation up- and down-canyon current regime (Puig et al., 2000) could have helped retaining sediment particles in the canyon interior, as they remain outside the influence of the geostrophic flow that just affects canyon-unconfined waters (Fig. 2).

Within the canyon, a thick near-BNL was also detected on May 1 (Fig. 9d), displaying the highest SSCs of the sampling period. The high concentration and thickness of this layer seem to be related to an up-canyon intrusion of WMDW (Fig. 5a), that could have favoured the retention at this depth range of sediment particles resuspended at the canyon axis fishing ground. The vertical oscillations of the water masses observed during the deployment had a frequency of 4-10 days, which are in agreement with the periodicity of the near-bottom along-canyon flow reversals observed by Puig et al. (2000) in this canyon. Even so, our data do not allow us to determine the concentration of this BNL at depths greater than 800 m due to the limited working range of the Aqualog (Fig. 2). Nonetheless, the SSC profile (Fig. 9d) suggests that the concentration tends to increase with depth. This limitation also prevented us to detect other potential BNLs developed by trawling activities along the canyon axis and that could have been extending closer to the bottom, without reaching the lower operational depths of the Aqualog.

Overall, our findings support the idea that resuspension induced by trawling activities can play a significant role in increasing SSC levels in the water column within the Foix Canyon, causing higher net particulate standing crop values as the number of hauls increases, whether they occur at canyon-confined or unconfined waters (Fig. 8).

4.2. Bottom-trawling as a major contributor in the formation of nepheloid layers in fished submarine canyons

There are many causes for the formation of nepheloid layers in the different oceans of the world (McCave, 1986). As it has been mentioned previously, in continental slope regions and submarine canyons, internal waves have been proposed as one of the major mechanisms that initiates sediment resuspension and, therefore, in generating nepheloid layers (Gardner, 1989; Puig and Palanques, 1998a; Puig et al., 2004; Martín et al., 2014a). The potential of internal waves in maintaining particles in suspension has been demonstrated in several studies (e.g. Gardner, 1989; Palanques and Biscaye, 1992; Puig et al., 2001). Submarine canyon morphologies can play a major role in determining the characteristics of internal waves' interaction with the seafloor and control suspended sediment particles transport at intermediate and deeper sectors of continental margins. Several studies have observed that some submarine canyons are shaped so they efficiently trap wave energy that, ultimately, can help to the generation of INLs at certain water depths (Gardner, 1989; Kunze et al., 2002; Puig et al., 2003). However, in open continental slope environments, it is difficult to observe this mechanism directly and to evaluate its contribution to the sediment dynamics. Indeed, in the Gulf of Valencia (western Mediterranean), where internal wave activity was properly characterised (van Haren et al., 2013), it was found that the presence of high SSC peaks recorded was unrelated to hydrodynamic processes, proposing trawling activities as the main sources of sediment resuspension on this area (Ribó et al., 2015). Previous hydrographic transects conducted on this area identified INLs and BNLs that by their water depth location were also attributed to trawling (Ribó et al., 2013).

Our data in the Foix Canyon corroborates that resuspension induced by trawling activities on slope and canyon environments can play a significant role as initiator of sediment resuspension at slope depths, generating INLs and BNLs at certain depths based on the locations of the fishing grounds. This mechanism might be particularly relevant in the Mediterranean Sea, where, in absence of tides, the internal wave activity is rather weak and occurs mostly at near-inertial frequencies.

Indeed, some previous observational field studies in the Mediterranean Sea, besides the previous described example of the Gulf of Valencia, have proposed trawling as a main driving force of sediment resuspension in continental slope regions. In the Catalan margin, Martín et al. (2014a) recorded the presence of nepheloid layers in a CTD+turbidimeter transect, conducted across a fishing ground in La Fonera Canyon. In the southern margin of the Aegean Sea (NE Mediterranean), Chronis et al. (2000) found near-BNLs and detached INLs in the vicinity of the shelf-break and over the upper slope region, suggesting that, besides near-bed current activity and breaking of internal waves, demersal fishing activities developed over the area might be likely causing the sharpest SSC recorded near the seabed. However, other studies in the Aegean Sea (e.g., Karageorgis and Anagnostou, 2003) have reported deep slope INLs in regions where fishing occurs at shallower depths. These authors attributed the formation of those INLs to natural processes, such as strong current velocities or internal waves. Therefore, both natural and anthropogenic mechanisms can coexist and generate sediment resuspension that, ultimately, can lead to the formation of nepheloid layers at continental slope depths.

Outside the Mediterranean, in the Whittard Canyon region (NE Atlantic), unusual high peaks of suspended particulate matter in nepheloid layers were also observed to be linked to trawling activities near the canyon (Wilson et al., 2015b, Daly et al., 2017). Through the use of VMS data, as in the present study, the locations and presence of bottom trawlers in the area provided evidence for the relationship between trawling

activity and the occurrence of enhanced nepheloid layers, that displayed anomalous high SSC values, exceeding those in the INLs typically observed in the region (Wilson et al 2015a).

Given that submarine canyons incising continental margins are often targeted by fisheries, it is likely that similar or other impacts have occurred and are occurring in other submarine canyons elsewhere in the world (Martín et al., 2014c; Oberle et al., 2018).

Bottom trawling has lately gained attention on the scientific community and policy makers (European Parliament, 2008), not only for the impacts on marine diversity and living resources, but also for its destructive effects on the seabed and its strong potential in altering sediment transport processes and turbidity conditions in the deep-sea environment at large spatial and time scales (Puig et al., 2012). The identification and assessment of these impacts, together with the quantification of the ecological status of the deep sea environment, has become increasingly important in Europe, especially after the implementation of the European Marine Strategy Framework Directive (MSFD; 2008/56/EC, descriptors #6 and #7) but it is still an ongoing challenge (Gislason et al., 2017). Accordingly, more measurements are necessary elsewhere to understand the effects of bottom trawling in deep ecosystems, including fished submarine canyons. Identifying and assessing the impacts of fishing activities could help us to reduce their negative effects.

5. Conclusions

Daily hydrographic profiles collected throughout this field study illustrate a well-defined water turbidity structure consisting in INLs, found between 300 and 500 m water depth and above the canyon rims at canyon-unconfined waters, and INLs and near-BNLs, confined within the canyon at depths greater than 650 m.

Using vessels' positioning through Vessel Monitoring System (VMS), the temporal and spatial distribution of the local trawling fleet over the study area at the time of the deployment strongly suggests that trawling resuspension is likely the major mechanism that leads to increasing SSCs in the water column. VMS logs revealed that the presence and water column levels of the observed nepheloid layers strongly depend on the operating depths of trawlers and on the specific fishing grounds being exploited.

Nonetheless, even bottom trawling appears to act as the main sediment resuspension mechanism, natural processes and ambient currents contribute to the advection and/or retention in suspension of resuspended particles, playing a major role in their transport along and across the margin via nepheloid layers.

The present study describes, for the first time, the temporal evolution of water column turbidity using an autonomous hydrographic profiler deployed at the canyon axis of a trawled submarine canyon on the NW Mediterranean region. Our study provides only a set of vertical profiles of the water column in the Foix Canyon, and more extensive studies are required to fully understand the turbidity structure at this or other comparable sites. For further studies, higher sampling frequency and working depth range of the hydrographic profiler would greatly increase our understanding of trawling-induced resuspension events.

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Figures

Fig. 1: Bathymetric map of the Catalan margin (NW Mediterranean) showing the location of the Foix Canyon, and the main fishing grounds and harbours. The red dot indicates the position of the mooring array used in this study. Blue dots represent Vessel Monitoring System (VMS) positions of trawlers during the monitoring period and the black arrow represents the geostrophic current. The white line depicts the transect showed in Figure 2.

Fig. 2: Bathymetric cross section and scheme of the mooring array deployed at the Foix canyon axis. See location in Figure 1.

Figure 3: Example of a suspended sediment concentration (SSC) profile with a strong nepheloid layer. The suspended matter which is in excess of the clear water minimum

(CWM) concentrations represents the net particulate standing crop (mg/cm^2) (grey-coloured area). SSCs below 800 m are not shown due to the limited working range of the Aqualog (See Fig. 2).

Figure 4: General θ -S diagram for all the CTD casts sampled in April-June 2014. (oAW: Old Atlantic Waters; LIW: Levantine Intermediate Waters; WMDW: Western Mediterranean Deep Waters). Colour scale indicates the depth from pressure (m).

Figure 5: Temporal variability of the vertical distribution of a) potential temperature, °C, and b) salinity, psu.

Figure 6: Temporal variability of the distribution of the suspended sediment concentration (SSC) during the monitoring period. Fishing days are indicated as blue bars on the bottom x-axis. SSC vertical profiles which were examined (Fig. 9a, b, c, d) are also shown in this figure.

Figure 7: Bathymetry of the eastern branch of the Foix canyon and the main fishing grounds. The red dot indicates the position of the mooring array used in this study. Blue dots represent Vessel Monitoring System (VMS) positions of trawlers during the monitoring period (a: first period, April 6 to April 15; b: second period, April 16 to April 25; c: third period, April 26 to May 5; d: fourth period, May 6 to May 15; e: fifth period, May 16 to May 25; f: sixth period, May 26 to June 2).

Figure 8: Relation between net particulate standing crop (mg/cm^2) and number of hauls from trawlers operating nearby the mooring location at the fishing grounds around the Foix Canyon (see Table 1). Linear relationships are shown for the (a) total computed net particulate standing crop and the total number of hauls, considering those at the axis and at the slope fishing grounds, and for the (b) computed net particulate standing crop at the slope (between the 200 and 500 m isobath) and the number of hauls counted at the slope fishing ground. Only fishing days were used to calculate the standing crop in both cases (see blue bars on the bottom x-axis of Fig. 6 for the exact dates).

Figure 9: Daily VMS recordings in the study area (blue dots) when nepheloid layers were absent (a) or present at different water depths: ~400 m (b), ~700 m (c) and near the bottom (d). See Fig. 6 for profile timing throughout the entire record.

	Period	Date (2014)	Fishing ground			
			Slope		Axis	
			# trawlers	# hauls	# trawlers	# hauls
Fig. 7a	1	April 6-April 15	5	10	0	0
Fig. 7b	2	April 16-April 25	6	12	4	7
Fig. 7c	3	April 26-May 5	5	13	5	13
Fig. 7d	4	May 6-May 15	12	52	9	32
Fig. 7e	5	May 16-May 25	13	38	6	15
Fig. 7f	6	May 26-June 2	12	45	6	14

Table 1: Main characteristics of the defined periods. Number of hauls (#) and number of trawlers (#) are presented for the identified fishing grounds. The first column indicates the correspondence with Figure 7.