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Evidence of large increases in sedimentation rates due to fish trawling in submarine canyons of the Gulf of Palermo (SW Mediterranean)

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ABSTRACT

Bottom trawling in submarine canyons can affect their natural sedimentation rates, but studies addressing this issue are still scarce. In the Gulf of Palermo (SW Mediterranean), bottom trawling occurs on the slope around Oreto, Arenella and Eleuterio canyons. Analyses of excess ^{210}Pb concentrations and grain size fractions in sediment cores from their canyon axes revealed that sedimentation rates and silt contents increased in all canyons in the 1980s, due to the expansion of more powerful trawlers (>500 HP) to deeper fishing grounds. In Eleuterio and Arenella canyons, sedimentation rates increased by an order of magnitude (0.1-1.4 $cm \cdot yr^{-1}$), whereas they increased less (0.1-0.7 $cm \cdot yr^{-1}$) in Oreto Canyon, since the enhanced trawling-derived sediment fluxes into this canyon are affected by sediment resuspension from trawling along its axis. Considering the global expansion of bottom trawling, we anticipate similar alterations in other trawled canyons, with ecological consequences that should be addressed by management strategies.

1. Introduction

Submarine canyons are geomorphological features that incise all continental margins (Harris and Whiteway, 2011), and are important pathways of particulate matter towards the deep-sea, serving as areas of preferential transport and accumulation of sediment (de Stigter et al., 2011; Liu et al., 2016; Maier et al., 2019). The high sedimentation rates in submarine canyons are mainly influenced by their capacity to intercept suspended particulate matter, especially during high-energy events such as storms, dense shelf water cascading, and river floods (Puig et al., 2014). Sediment transport in canyons also increases from occasional canyon-slope failures, evolving into large-scale sediment gravity flows (Talling, 2014).

There is increasing evidence that sedimentation processes in submarine canyons can also be altered by bottom trawling activities, since the contact of the heavy trawling gear with the seafloor can resuspend large volumes of sediment (Depestele et al., 2016; O'Neill and Ivanovic, 2016). Recent studies have shown that when this type of fishery occurs in areas within and around submarine canyons, sediment resuspended by bottom trawling gear can be transferred into them as enhanced nepheloid layers (Martín et al., 2014c; Wilson et al., 2015; Arjona-Camas et al., 2019), or as dilute sediment gravity flows (Palanques et al., 2006a, 2006b; Puig et al., 2012; Martín et al., 2014b). The transfer of trawled sediment into canyons has caused sedimentation rates in canyon axes to increase since the expansion of bottom trawling fleets towards continental slope and canyon flank regions (Martín et al., 2008; Puig et al., 2015; Paradis et al., 2017, 2018a, 2018b). These impacts are particularly important in areas that are directly down-slope and down-current from fishing grounds, with trawling-associated sedimentation rates decreasing with distance from them (Paradis et al., 2018b). Although increases in sedimentation rates have only been reported in canyons incising the NW Mediterranean margin, it is expected that many trawled canyons have become anthropogenic sediment depocenters, since even non shelf-incising canyons with little capacity to intercept suspended sediment from the shelf experienced similar modifications (Paradis et al., 2017). Considering that bottom trawling grounds have

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been expanding from shallow to deeper environments at a global scale since the 1950s (Norse et al., 2012; Watson and Morato, 2013), generally occurring close to and along submarine canyons due to their high biomass and biodiversity (Fernandez-Arcaya et al., 2017), further studies are needed to determine whether similar alterations of sedimentation rates occur in other trawled submarine canyons, which could cause ecological perturbations to the fragile ecosystems inhabiting them (Pusceddu et al., 2014; Román et al., 2016, 2017; Lastras et al., 2016; De Leo et al., 2019; Bilan et al., 2020).

The Gulf of Palermo, NW Sicily (SW Mediterranean), is incised by several submarine canyons (Lo Iacono et al., 2011, 2014). This region supports bottom trawling grounds on the outer shelf and upper slope sectors surrounding the head of submarine canyons, and along the axis of Oreto Canyon (Fig. 1). Studies on the sedimentary regimes in this Gulf are scarce and limited to the shelf (Di Leonardo et al., 2007; Rizzo et al., 2009), and the potential relationship between bottom trawling and sedimentation rates has not been explored yet. The main aim of this work is to provide a general overview of modern sedimentary regimes in the Gulf of Palermo and in its canyons, and assess how bottom trawling may have modified sedimentation rates in the area. This is achieved by estimating the historical evolution of bottom trawling effort using their engine power, since it reflects the capacity of disturbance of the seafloor and their maximum fishing depth (Ragnarsson and Steingrimsson, 2003; Martín et al., 2014b), and the analyses of sediment grain size and excess ^{210}Pb, a natural radioactive tracer used to determine sedimentation rates, in sediment cores collected within canyons (Fig. 1).

2. Methodology

2.1. Study site

The Gulf of Palermo is located in the north-western Sicilian margin and is delimited by Cape Gallo to the west and by Cape Zafferano to the east, with a total surface of 250 km^2 (Fig. 1). The most important rivers that discharge into the gulf are the Oreto and Eleuterio rivers, with an average discharge of 0.25 $m^3 \cdot s^{-1}$ that can increase to 5.3 $m^3 \cdot s^{-1}$ and 26.3 $m^3 \cdot s^{-1}$, respectively, during storm events (Mannina and Viviani, 2010; Billi and Fazzini, 2017).

Since the Mediterranean is a semi-enclosed sea, the study area presents a micro-tidal regime, and a regional cyclonic geostrophic current flows from west to east, parallel to the coastline (Istituto Idrografico della Marina, 1982) (Fig. 1). Sediment grain size on the shelf is coarser towards the northwest and at the river mouths, mainly consisting of sand, and shows a general fining trend towards the south east (Tranchina et al., 2008), following the general pattern of current circulation. Modern sedimentation rates in the Gulf of Palermo have only been estimated in the shelf, and range from 0.58 $cm \cdot yr^{-1}$ in the inner shelf to 0.21 $cm \cdot yr^{-1}$ in the outer shelf (Di Leonardo et al., 2007; Rizzo et al., 2009).

The continental shelf presents an average width of 8 km, and is

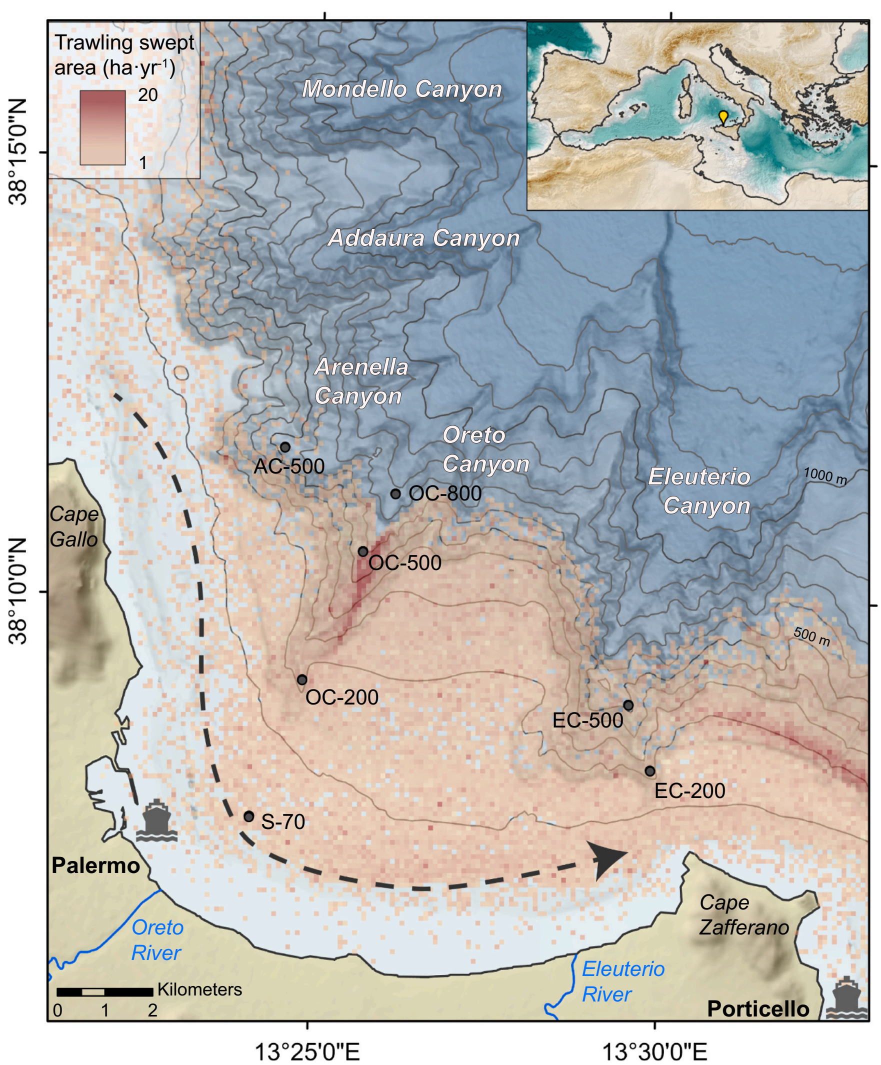

Fig. 1. Bathymetric map of the Gulf of Palermo, with the three main submarine canyons incising the margin (Arenella, Oreto, and Eleuterio canyons) as well as the location of sediment cores sampled. Mean annual trawling intensity is given as swept area per year between 2008 and 2016. The location of the main harbors (Palermo and Porticello) and the most important rivers discharging into the Gulf are also given. The dashed line shows the direction of the regional current and contour lines are displayed every 100 m.

delimited by the shelf-edge at a depth of 120-130 m. The continental slope is incised by five main submarine canyons (Mondello, Addaura, Arenella, Oreto and Eleuterio), with downslope gradients ranging from 6° to 13°, that are connected at the base of the intra-slope basin at 1000-1500 m depth (Lo Iacono et al., 2011; Fig. 1). The most important canyons in the Gulf are Oreto and Eleuterio canyons (Fig. 1). Oreto Canyon displays a linear to sinuous head that indents the shelf-edge at the central sector of the Gulf (Fig. 1), and developed in connection with the Oreto River (Lo Iacono et al., 2011). Eleuterio Canyon to the east is the largest canyon of the Gulf (Fig. 1), and there are no evidences of its connection to the Eleuterio River (Lo Iacono et al., 2014). The geomorphology of its head is widened by several mass wasting processes along its walls (Lo Iacono et al., 2011, 2014). Its axial incision is directed towards Cape Zafferano (Fig. 1), reducing the distance from the shore to ~2 km, which favors the transport of suspended sediment from the shelf into this canyon. Both Eleuterio and Oreto cayons present tectonically-controlled obstructions at 750 and 600 m depth, respectively (Lo Iacono et al., 2014, 2011). The submarine canyons located in the northwestern sector of the gulf, Arenella, Addaura and Mondello canyons, are steeper and shorter, and incise the edge of the continental shelf (Fig. 1; Lo Iacono et al., 2011). The evolution of these three canyons has been ascribed to stacked landslides retrograding from the base of the slope to the shelf domain (Lo Iacono et al., 2011).

Bottom trawling fleets operating in this margin originate from Porticello and Palermo harbors (Fig. 1). Trawling grounds are located on the outer shelf and on the upper slope between Oreto an Eleuterio canyons, at 50 to 700 m depth range (Fig. 1). Trawlers often perform hauls along the axis of Oreto Canyon, mostly between ~200 and ~700 m depths, limited by the presence of a tectonic high at 750 m depth that prevents bottom trawlers to progress further downcanyon. (Fig. 1). No other canyons in the Gulf of Palermo are trawled along their axes, and the vessels' heading from the VMS data indicate that the trawl hauls on the continental slope are conducted along margin, following the isobaths.

2.2. Sampling

In the framework of ISLAND (ExplorIng SiciLian CAnyoN Dynamics) cruise on board the R/V Angeles Alvariño, funded by the EU-FP7 Eurofleets2 Project (GA 31272), seven sediment cores were collected in August 2016 from the Gulf of Palermo continental shelf and from the axes of Arenella, Oreto and Eleuterio canyons (Table 1, Fig. 1). Sediment cores, with a length ranging from 39 to 56 cm, were collected using a K/C Denmark A/X six-tube multicore (inner diameter 9.4 cm), and the core with the best preservation of the sediment-water interphase was subsampled at 1 cm interval. These subsamples were then stored in sealed plastic bags at -20 °C until freeze-dried in the laboratory for analyses. Replicate cores weren't collected for the analysis of sediment grain size

Table 1
Sediment core sampling date and location.

Core	Location	Coordinates		Depth (m)	Sampling date
		Latitude (N)	Longitude (E)		
S-70	Inner shelf	38.1248	13.4018	72	15/08/2016
OC-200	Upper Oreto Canyon	38.1509	13.4140	223	15/08/2016
OC-500	Mid-Oreto Canyon	38.1754	13.4281	574	10/08/2016
OC-800	Lower Oreto Canyon	38.1864	13.4357	770	15/08/2016
EC-200	Upper Eleuterio Canyon	38.1347	13.4978	242	08/08/2016
EC-500	Mid-Eleuterio Canyon	38.1471	13.4924	518	08/08/2016
AC-500	Arenella Canyon	38.1949	13.4090	544	16/08/2016

and sedimentation rates, as they rarely present spatial variability at small spatial scales (Nittrouer et al., 1979; Gordon and Goñi, 2004; DeGeest et al., 2008; de Stigter et al., 2011). A sediment core was collected on the shelf at 72 m water depth (S-70), ~2.5 km off the Oreto River mouth. Since bottom trawlers often operate along the axis of Oreto Canyon, this canyon was sampled at ~200, ~500, ~800 m depths (OC-200, OC-500, OC-800). Sediment cores were collected at ~200 and ~500 m depths in Eleuterio Canyon (EC-200, EC-500), whereas in the smaller Arenella Canyon, only one sediment core was collected at ~500 m water depth (AC-500) (Fig. 1).

2.3. Analytical techniques

Grain size fractions were determined using a Horiba Partica LA950V2 particle size analyzer by previously oxidizing 1-4 g of dried sediment using 20% H_2O_2 and disaggregating it using 2.5% $P_2O_7^{4-}$.

Total ^{210}Pb concentrations were obtained through alpha spectroscopy of its decay product ^{210}Po, assuming secular equilibrium of both radionuclides prior to the analysis, following the method described by Sánchez-Cabeza et al. (1998). Briefly, between 150 and 300 mg of homogenized dried sediment were spiked with a tracer of ^{209}Po before microwave acid-digestion with HNO_3, HF, and H_3BO_3. The resulting solutions were evaporated and re-conditioned with 1 M HCl. Polonium isotopes were spontaneously plated on silver disks while stirring at 70 °C for 8 h. Alpha emissions of ^{209}Po (4883 keV) and ^{210}Po (5304 keV) were quantified using passivated implanted planar silicon (PIPS) detectors (CANBERRA, model PD-450.18 A.M.) and the Genie™ data acquisition software. Excess ^{210}Pb concentrations were obtained by subtracting supported ^{210}Pb concentrations from the total ^{210}Pb concentrations. Supported concentrations of ^{210}Pb of each sediment core were obtained by averaging constant concentrations of total ^{210}Pb concentrations from the bottom of each core, assuming all excess ^{210}Pb had decayed. Supported ^{210}Pb concentrations obtained through this approach in the sediment cores (M = 32 Bq·kg^{-1}, SD = 4 Bq·kg^{-1}) are comparable to those reported in sediment cores collected in the Mediterranean (Masqué et al., 2003; Barsanti et al., 2011), as well as those reported in sediment cores from the adjacent Gulf of Castellammare (Paradis et al., 2019).

Average sedimentation rates over the last century were calculated from the excess ^{210}Pb concentration profile over cumulative dry mass, to correct for sediment compaction with depth, using the Constant Flux Constant Sedimentation model described by Krishnaswamy et al. (1971). Excess ^{210}Pb concentration profiles often present a shift in slope in its upper sections, caused by physical mixing by bottom currents or bioturbation processes. In these cases, the excess ^{210}Pb profile is interpreted as a two-layer system, with an upper surface mixed layer (SML) and a constant sedimentation with negligible mixing in the lower layer, where the CF:CS model is applied (Nittrouer et al., 1979). Since mixing can also modify the excess ^{210}Pb slope with depth, sedimentation rates need to be regarded as upper estimates. Changes in average sedimentation rates were evaluated by observing variations in the excess ^{210}Pb slope that could not be explained by surface mixing (i.e. an excessively deep SML, or an excessively old excess ^{210}Pb horizon). In these cases, the CF:CS model is applied piece-wise, estimating mean sedimentation rates over each layer. Sections with constant excess ^{210}Pb concentrations were attributed to the instantaneous arrival of allochthonous sediment from the canyon walls, and were not included in the dating model (Garcia-Orellana et al., 2006; de Stigter et al., 2011).

2.4. Bottom trawling grounds and historical evolution of fishing effort

The distribution of bottom trawling grounds was determined from Vessel Monitoring System (VMS) data, a mandatory transmitter since 2005 in all European vessels with a length overall equal to or greater than 15 m (European Commission, 2003). VMS sends information of the vessel's position, speed, and heading to the network of coastal guard by Inmarsat-C at about 1-2 h intervals. In principle, the relatively low sampling frequency of VMS can be overcome by using the higher sampling frequency of Automatic Identification System (AIS), which emit vessel positioning at 1-5 min intervals. However, AIS can underestimate fishing effort due to interferences when emitting signals or because fishing vessels turn off their AIS emitter to purposefully hide their fishing grounds (Russo et al., 2016; Shepperson et al., 2018). In addition, Russo et al., 2019 reports an extensive assessment of trawl fishing effort in the Italian waters demonstrating that VMS still represents the most reliable tracking device and that the potentially missed trawling effort from VMS-based estimates (but captured by AIS) would be less than 5%. Considering also that AIS provides only 19% of Italian fishing vessel coverage in comparison to the 94% coverage of VMS data (Russo et al., 2016), trawling intensity was estimated using VMS data. To overcome the low sampling frequency, vessel positioning was interpolated based on its speed, heading, and accounting for its drift using the R package VMSbase (Russo et al., 2014). Trawling intensity, expressed as mean swept area in hectares, was estimated using VMS data from 2008 to 2016 in the Gulf of Palermo in 100 m^2 grid cells (Russo et al., 2014). Although the low spatial resolution and positioning frequency of trawling activities recorded by VMS can be too coarse to generate such a fine-scale grid, it allowed us to define the extension of the fishing effort along the Oreto Canyon (Fig. 1).

Considering that VMS data is only available since 2008, historical evolution of fishing effort of bottom trawlers registered in Porticello and Palermo harbors was estimated from trawlers' total engine power (horsepower; HP). Engine power can be used as an indicator of the depth range of bottom trawling grounds, since trawlers require bigger and heavier gear to fish at greater depths, which is limited by the vessel's engine power (Ragnarsson and Steingrimsson, 2003; Martín et al., 2014b). Moreover, gear weight and its hydrodynamic drag influence the capacity to stir and resuspend sediment, which are also proportional to vessel's engine power (O'Neill and Ivanovic, 2016). Historical (1900-2016) engine power of bottom trawlers of Porticello and Palermo harbors was obtained from the European Union's Fishing Fleet Register database (Maritime Affairs and Fisheries, 2020) by filtering for fishing vessels with otter trawl boards (OTB) as their main or secondary gear.

3. Results

3.1. Sedimentological properties and sedimentation rates

3.1.1. Outer shelf

The sediment core collected in the outer shelf at a depth of 72 m (S-70) presented a 4 cm surface mixed layer, and an average sedimentation rate of 0.166 ± 0.007 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.203 ± 0.009 $cm\cdot yr^{-1}$) was estimated below (Fig. 2; Table 2). This core was composed of mostly silt (65%), clay (30%), and some sand fraction (5%). Sediment grain size presented a slight upwards coarsening trend due to an increase of silt content from 55% at the base of the core to 71% at its surface (Fig. 2).

3.1.2. Oreto Canyon

Farther offshore, in the trawled Oreto Canyon, the excess ^{210}Pb concentration profiles in the three sediment cores presented distinctively different slopes within core depth, indicative of changes in sedimentation rates (Fig. 2). Although all sediment cores are composed of mostly silt (~51%), clay (~47%) and low sand (~2%) fractions, they all presented an upwards coarsening trend due to an increase in silt fraction that occurred in coincidence with the shift in excess ^{210}Pb concentration profile (Fig. 2).

In the case of OC-200, an average sedimentation rate of 0.121 ± 0.007 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.157 ± 0.009 $cm\cdot yr^{-1}$) was estimated for the lower section (21-29 cm), which had 52% of silt. In the upper 21 cm, sedimentation rates nearly tripled to 0.30 ± 0.02 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.59 ± 0.03 $cm\cdot yr^{-1}$), with an increase in silt fraction to 61% that further increased to ~80% in the upper 3 cm of the core (Fig. 2; Table 2). In OC-500, an average sedimentation rate of 0.077 ± 0.005 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.114 ± 0.007 $cm\cdot yr^{-1}$) was estimated for the lower section (32-41 cm), which had 43% of silt. This section was overlain by a section (25-32 cm) with constant excess ^{210}Pb concentrations of 120 ± 10 $Bq\cdot kg^{-1}$ and slightly greater silt content of 47%. Above, a higher sedimentation rate of 0.35 ± 0.03 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.73 ± 0.05 $cm\cdot yr^{-1}$) was quantified, coincident with an upward increment of sand (3 to 8%) and silt (57 to 72%) content towards the surface (Fig. 2; Table 2). Similarly, in OC-800, a lower average sedimentation rate of 0.074 ± 0.004 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.110 ± 0.006 $cm\cdot yr^{-1}$) was quantified in the deeper section (14-26 cm) with 0.8% sand and 45% silt content. This core also presented a section (7-14 cm) with constant excess ^{210}Pb concentrations of 129 ± 18 $Bq\cdot kg^{-1}$ that had higher sand and silt content of 4% and 51%, respectively (Table 2). Overlaying this section, sedimentation rate doubled to 0.111 ± 0.006 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.210 ± 0.012 $cm\cdot yr^{-1}$) in the upper 7 cm, with a greater increase in silt fraction (60%) that reached ~82% in the upper 3 cm (Fig. 2; Table 2). Assuming that the sections with constant excess ^{210}Pb concentrations represent instantaneous sediment pulse-events, the changes in sedimentation rates observed from the excess ^{210}Pb concentration profiles in these three sediment cores occurred simultaneously in the early 1980s.

3.1.3. Eleuterio Canyon

In the eastern-most Eleuterio Canyon, the sediment core collected in the canyon axis at ~200 m depth (EC-200) was 41 cm long but supported ^{210}Pb concentrations were not reached. Its excess ^{210}Pb concentration profile presented a 4 cm surface mixed layer coinciding with high sand (5%) and silt (74%) content, overlaying a constant decrease in excess ^{210}Pb concentrations from which an average sedimentation rate of 0.38 ± 0.02 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.52 ± 0.02 $cm\cdot yr^{-1}$) was estimated, with lower sand (2%) and silt (61%) content (Fig. 2; Table 2). The base of the profile (36-41 cm) presented constant excess ^{210}Pb concentrations of 43 ± 4 $Bq\cdot kg^{-1}$ and would have accumulated in the early 1950s, with even finer sediment grain size consisting of lower sand (1%) and silt (57%) content.

The excess ^{210}Pb concentration profile of the sediment core collected farther downcanyon at ~500 m (EC-500), showed a lower sedimentation rate of 0.083 ± 0.005 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.114 ± 0.006 $cm\cdot yr^{-1}$) in the deeper section (43-50 cm) that then increased by an order of magnitude to 0.82 ± 0.04 $g\cdot cm^{-2}\cdot yr^{-1}$ (1.38 ± 0.07 $cm\cdot yr^{-1}$) in the mid-1980s (Fig. 2; Table 2). Although this sediment core consisted of mostly silt (54%) and clay (44%) with low sand (2%), the upper 4 cm presented an evident grain size coarsening due to an increase in silt fraction to ~80% (Fig. 2; Table 2).

3.1.4. Arenella Canyon

The excess ^{210}Pb concentration profile of the sediment core collected at ~500 m depth in Arenella Canyon (AC-500) also indicates a shift from a lower sedimentation rate of 0.088 ± 0.005 $g\cdot cm^{-2}\cdot yr^{-1}$ (0.131 ± 0.007 $cm\cdot yr^{-1}$) in the lower sections (36-45 cm) that increased by an order of magnitude to 0.74 ± 0.04 $g\cdot cm^{-2}\cdot yr^{-1}$ (1.37 ± 0.07 $cm\cdot yr^{-1}$) in the upper 36 cm. According to the dating model, the change in sedimentation rates occurred around the late 1980s (Fig. 2; Table 2). In the lower section (36-45 cm), sediment had sand and silt contents of 5% and 47%, respectively, with an upwards coarsening trend due to an increase in sand and silt contents to 9% and 59%, respectively, coinciding with the shift in sedimentation rate. Finally, as observed in the majority of the sediment cores, sediment had the highest silt content (~80%) in the upper 4 cm (Fig. 2).

3.2. Evolution of trawling effort

The evolution of the trawling fleets registered in Porticello and Palermo harbors is presented in Fig. 3. According to official records, the first bottom trawlers were constructed in the late-1950s, with a continuous growth of the fishing fleets throughout the 1960s and 1970s, mostly belonging to Porticello harbor (Fig. 3a, b). By 1980, there were 63 trawlers from Porticello and only 7 trawlers from Palermo, and the

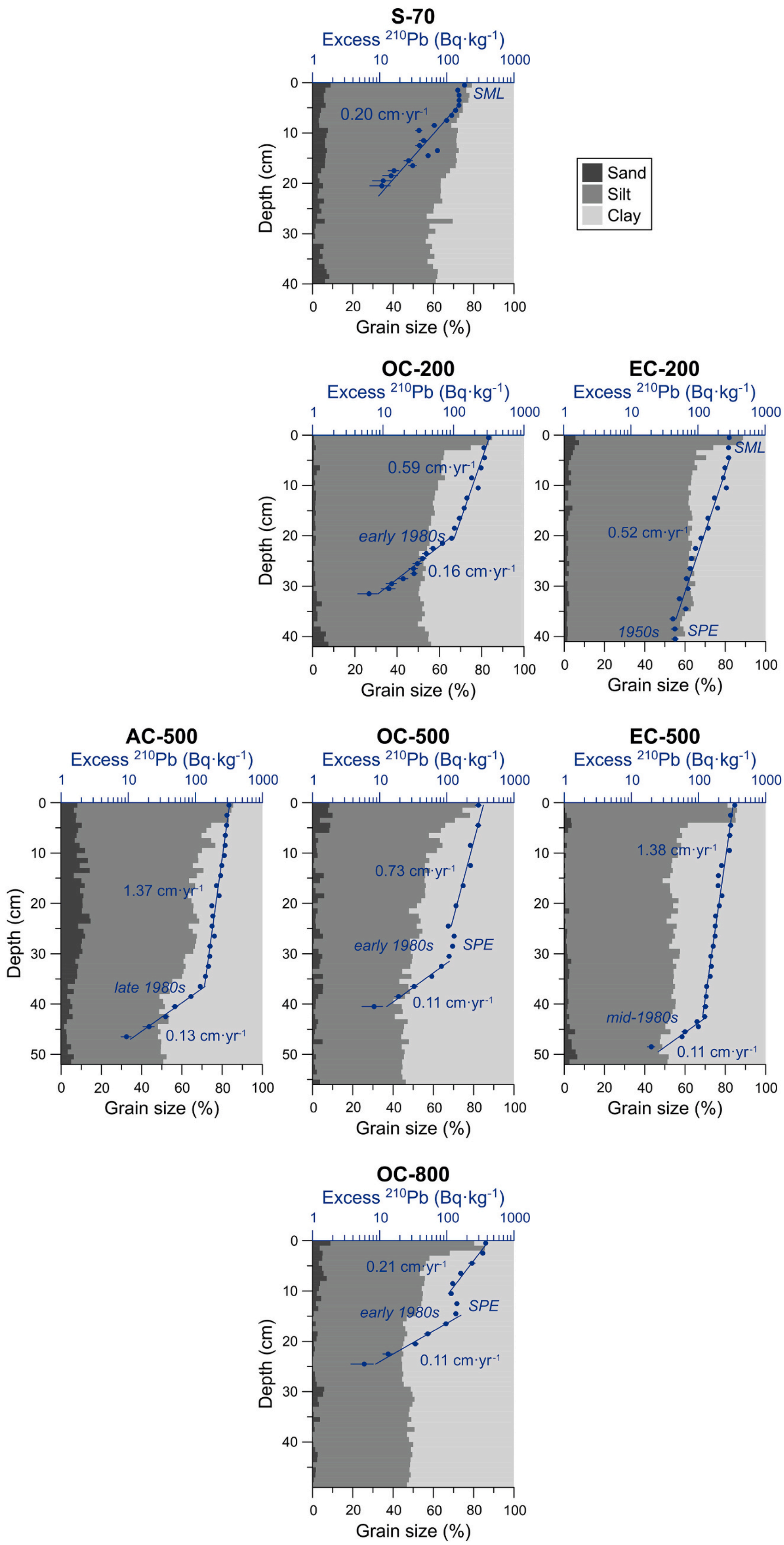

Fig. 2. Excess ^{210}Pb concentration profiles (blue) and the estimated average sedimentation rates (refer to Table 2 for full data of accumulation rates), and grain size fractions (grey scale) of sediment cores collected in the shelf (S-70), Arenella Canyon (AC-500), Oreto Canyon (OC-200, OC-500, OC-800), and Eleuterio Canyon (EC-200, EC-500). Note that the excess ^{210}Pb concentration profiles are represented based on sediment core depth, whereas the CF:CS model used to determine sedimentation rates was performed using cumulative dry mass (see Methodology). SML = surface mixed layer; SPE = sediment pulse event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Main sedimentological and radiochemical parameters of each sediment core.

Core	Length (cm)	Sections (cm)	Grain size fraction (%)			Sedimentation rates		
			Sand	Silt	Clay	MAR ($g \cdot cm^{-2} \cdot yr^{-1}$)	SAR ($cm \cdot yr^{-1}$)	Year[a]
S-70	39	0-4	7	71	22	Surface mixed layer		
		4-21	5	65	30	0.166 ± 0.007	0.203 ± 0.009	
OC-200	42	0-21	1	61	38	0.30 ± 0.02	0.59 ± 0.03	Early 1980s
		21-29	1	52	47	0.121 ± 0.007	0.157 ± 0.009	
OC-500	56	0-25	3	57	40	0.35 ± 0.03	0.73 ± 0.05	
		25-32	3	47	50	Sediment pulse-event		Early 1980s
		32-41	3	43	54	0.077 ± 0.005	0.114 ± 0.007	
OC-800	49	0-7	5	60	35	0.111 ± 0.006	0.210 ± 0.012	
		7-14	4	51	45	Sediment pulse-event		Early 1980s
		14-26	1	45	54	0.074 ± 0.004	0.110 ± 0.006	
EC-200	41	0-4	5	74	21	Surface mixed layer		
		4-36	2	61	37	0.38 ± 0.02	0.52 ± 0.02	
		36-41	1	57	42	Sediment pulse-event		Early 1950s
EC-500	50	0-43	1	56	43	0.82 ± 0.04	1.38 ± 0.07	Mid 1980s
		43-50	3	47	50	0.083 ± 0.005	0.114 ± 0.006	
AC-500	52	0-36	9	59	32	0.74 ± 0.04	1.37 ± 0.07	Late 1980s
		36-45	5	47	48	0.088 ± 0.005	0.131 ± 0.007	

[a] Approximate date of event (sediment pulse-event and/or change in sedimentation rate) according to the ^{210}Pb dating model.

total engine power of the trawling fleets were ~14,000 HP and ~1,500 HP, respectively (Fig. 3a, c). Despite this clear difference in both harbors at that time, their fishing fleet had a similar average engine power of ~200 HP (Fig. 3d).

During the 1980s, fishing fleets of Palermo and Porticello presented their greatest expansion, with the addition of 60 new trawlers in Porticello and 13 new trawlers in Palermo, causing total engine power to grow to ~25,000 HP and ~8,400 HP for each trawling fleet (Fig. 3a, b, c). Despite this contrasting expansion, average horsepower of the Porticello trawling fleet remained constant at ~200 HP whereas it drastically increased to ~500 HP for the Palermo trawling fleet (Fig. 3d).

During the following decades, the Porticello trawling fleet decreased in size due to the dismantling of 59 small trawlers, leading to a decrease of total horsepower from ~25,000 HP in 1990 to ~17,000 HP in 2016, but maintaining average engine power at ~200 HP (Fig. 3). In the case of trawling fleet registered in Palermo, the construction of 26 trawlers during the early 2000s contributed to the increase of total engine power of this trawling fleet, reaching maximum values of ~29,000 HP in the mid-2000s, with average engine power increasing to ~700 HP (Fig. 3). Since the mid-2000s, Palermo trawling fleet also declined, although average engine power remained relatively constant at ~700 HP (Figs. 3).

The decadal distribution of engine power of each trawling fleet illustrates the shift towards more powerful bottom trawlers since the 1980s (Fig. 4). During that decade, 5 new trawlers with engine power greater than 500 HP were incorporated to the Palermo trawling fleet, with 3 exceptionally large trawlers (1000-1500 HP). This trend continued during the following decades, with an increasing number of more powerful bottom trawlers being incorporated to the Palermo trawling fleet, such as the addition of 4 new trawlers with engine power between 1500 and 2000 HP during the 2000s (Fig. 4). In contrast, during the whole period, Porticello trawlers consisted of generally smaller vessels with engine power in the range of 50-500 HP (Fig. 4).

4. Discussion

Previous studies assessing sedimentary regimes in the continental shelf of the Gulf of Palermo show highest sedimentation rates in the inner shelf (0.58 $cm \cdot yr^{-1}$), at 36 m depth and at less than 1 km from the Oreto River mouth (core GP, Rizzo et al., 2009), and a decrease to 0.21 $cm \cdot yr^{-1}$ in the outer shelf, at 98 m (core BC12, Di Leonardo et al., 2007). A similar sedimentation rate (0.20 $cm \cdot yr^{-1}$) was obtained from the outer shelf sediment core collected at 72 m water depth for this study (S-70; Fig. 5), confirming the decreasing trend in sedimentation rates across the Palermo continental shelf, as observed in other continental margins (Gordon and Goñi, 2003; Miralles et al., 2005).

The off-shore decreasing trend of natural (i.e., pre-industrialization of the trawling activities) sedimentation rates across the Gulf of Palermo is reflected by the sedimentation rates observed in the lower sections of the cores taken at Arenella and Oreto canyons, decreasing from 0.16 $cm \cdot yr^{-1}$ at ~200 m depth (OC-200) to 0.11 $cm \cdot yr^{-1}$ at ~500 m in both canyons (AC-500 and OC-500) and at ~800 m in Oreto Canyon (OC-800) (Figs. 2, 5). However, this across-margin spatial pattern contrasts with the high sedimentation rates estimated at the head of Eleuterio Canyon (EC-200; 0.52 $cm \cdot yr^{-1}$). These higher rates can be explained by the transport of shelf suspended sediment by the regional cyclonic circulation until reaching Cape Zafferano (Fig. 5). This promontory redirects currents towards the head of Eleuterio Canyon, transferring large amounts of particulate matter (Fig. 5; Lo Iacono et al., 2014). In addition to these higher natural sediment fluxes, mass failures are frequent in this canyon (Lo Iacono et al., 2011, 2014), which may explain the 5 cm-thick sediment pulse-event interpreted at the base of the EC-200 core, dated to the 1950s (Fig. 2; Table 2). In fact, high sediment fluxes generally occur in canyons located close to headlands, as is the case of Cap de Creus Canyon (Palanques et al., 2006a, 2006b), Monterey Canyon (Maier et al., 2019), and Nazaré Canyon (de Stigter et al., 2011), as currents are constrained by the physiography of these promontories and forced to flow towards the canyon head. This natural transport of sediment along the shelf and into Eleuterio Canyon could also include sediment resuspended by trawling activities on the shelf (Churchill, 1989; Ferré et al., 2008; Palanques et al., 2014; Oberle et al., 2016b), which have been occurring on the Gulf of Palermo since the 1950s by small bottom trawlers (Figs. 1, 4). Despite the presence of trawling activities on the shelf, S-70 core did not present any significant alterations in its excess ^{210}Pb profile, indicating minimal impact of bottom trawling gear on the seafloor associated to the low trawling frequency of the smaller and less powerful bottom trawlers operating on the shelf, as observed on certain sites of the NW Iberian shelf (Oberle et al., 2016a).

In the remaining sediment cores collected in the canyon axes, a shift in their excess ^{210}Pb concentration profiles indicates an increase in sedimentation rates occurring simultaneously in the 1980s (Fig. 2). This

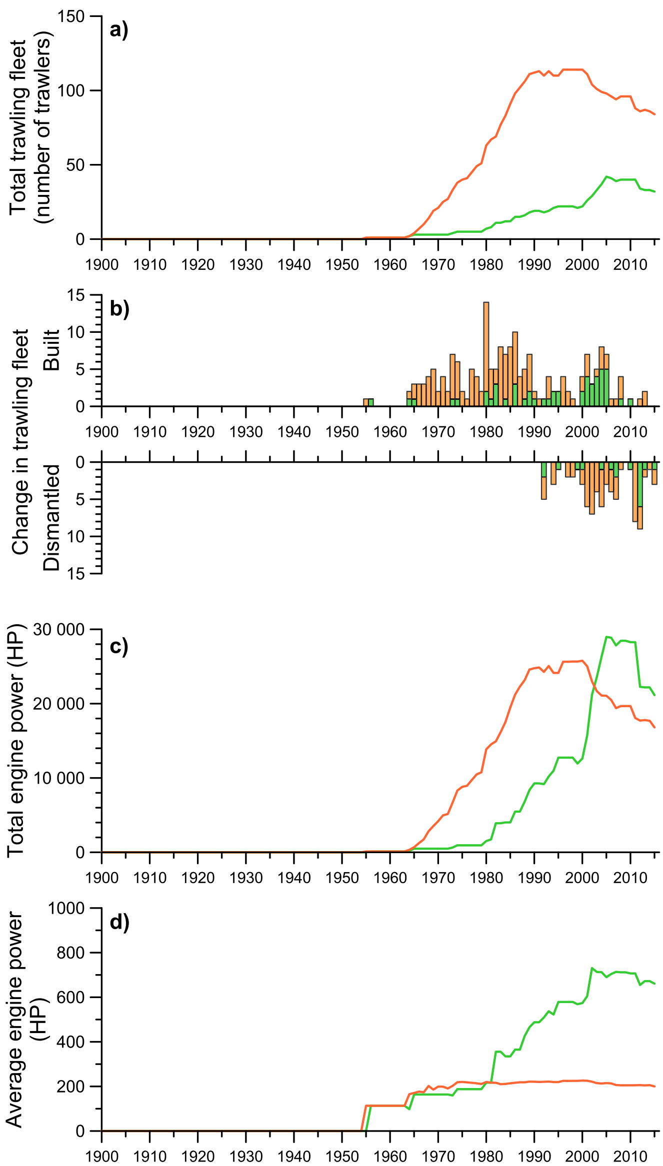

Fig. 3. Evolution of the trawling fleets of Palermo (green) and Porticello (orange) between 1900 and 2016 in terms of (a) total trawling fleet, (b) number of built and dismantled trawlers, (c) total engine power, and (d) average engine power. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

regional enhancement of sedimentation rates in the submarine canyons incising the Gulf of Palermo occurred in coincidence with the period of greatest growth of the bottom trawling fleets of Palermo and Porticello harbors (Fig. 3). During the 1980s, Palermo trawling fleet incorporated more powerful bottom trawlers (500-1000 HP; Fig. 4) that could carry heavier bottom trawling gear which are necessary to operate at deeper environments (Ragnarsson and Steingrimsson, 2003; Norse et al., 2012; Martín et al., 2014b). Hence, it is quite likely that since the 1980s, the larger bottom trawlers registered in Palermo harbor opened new and deeper fishing grounds on the continental slope sectors of the Gulf of Palermo, whereas the smaller bottom trawlers from Porticello harbor would have remained fishing on the shelf (Fig. 1). Considering the capacity of heavy bottom trawling gear to resuspend sediments (Puig et al., 2012; O'Neill and Ivanovic, 2016; Oberle et al., 2016b), the expansion of bottom trawling grounds towards the open slope areas surrounding canyons would have transferred sediment towards their axes. Hence, this expansion caused natural sedimentation rates of Palermo canyons, which range between 0.11 and 0.16 cm·yr^{-1}, as typically observed in other Mediterranean canyons (Sanchez-Cabeza et al., 1999; DeGeest et al., 2008; Paradis et al., 2018b), to increase to maximum values of ~1.4 cm·yr^{-1} since the 1980s (Figs. 2, 5).

This general shift in sedimentation rates cannot be attributed to changes in precipitation regimes nor increases in sediment river discharge in the area. Studies of changes in precipitation regimes in Sicily have observed a general decrease in yearly precipitation (Cannarozzo et al., 2006; Arnone et al., 2013), which leads to a general decrease in the discharge of both Oreto and Eleuterio rivers (Billi and Fazzini, 2017), with a similar effect in sediment yield. Moreover, the S-70 sediment core collected ~2.5 km from the Oreto River in the outer shelf presented a constant sedimentation rate of 0.20 cm·yr^{-1} over the last century (Fig. 2; Table 2). This indicates that sediment discharge into the Gulf of Palermo during this period didn't increase, or at least that any potential change has not been registered in the outer shelf deposits. Hence, the most plausible explanation of the shift in sedimentary regimes observed in all submarine canyons is the coeval expansion of bottom trawling grounds to deeper areas, where resuspended sediment by this activity is ultimately accumulated inside the canyons (Fig. 5).

These trawling-derived increases in sedimentation rates occurred similarly in two of the studied submarine canyons. In Eleuterio Canyon, at ~500 m depth, sedimentation rates increased from 0.11 to 1.38 cm·yr^{-1} in the mid-1980s, while at the same depth in Arenella Canyon, sedimentation rates increased from 0.13 to 1.37 cm·yr^{-1} in the late 1980s (Fig. 5; Table 2). The similar trawling-derived sedimentation rates in both canyons indicate that they intercept comparable volumes of resuspended sediment by trawling on the adjacent continental slope sectors (Fig. 5), presumably as concentrated nepheloid layers advected over the canyon (Martín et al., 2014c; Wilson et al., 2015; Arjona-Camas et al., 2019).

In contrast, in the trawled Oreto Canyon, the trawling-derived sedimentation rates at ~500 m depth increased from 0.11 to 0.73 cm·yr^{-1} (Figs. 2, 5; Table 2). Despite that this seven-fold increase in sedimentation rate is still significant, it is relatively lower in comparison to the order of magnitude increase observed in Arenella and Eleuterio canyons. This lower trawling-derived sedimentation rate in Oreto Canyon is attributed to trawling activities conducted along its axis, which would induce local sediment resuspension that would then be transported farther downcanyon, and hence reduce the net accumulation rate at ~500 m depth (Fig. 5). This is supported by the doubling of sedimentation rates from 0.11 to 0.21 cm·yr^{-1} at ~800 m within the canyon (OC-800), which is located beyond the trawled canyon axis (Fig. 5). In fact, the tectonic high located at 750 m in the axis limits trawling grounds, because these geomorphological obstructions promote gear loss (Brennan et al., 2016; Eigaard et al., 2017; Richardson et al., 2018). Hence, the downcanyon transferal of suspended sediment by bottom trawling along the canyon axis increased sedimentation rates in even deeper areas located farther offshore.

Prior to these increases in sedimentation rates, constant excess ^{210}Pb concentrations in OC-500 and OC-800 indicate the arrival of a sedimentary pulse-event that would have likely been associated to the initial expansion of bottom trawling grounds into this canyon in the 1980s. The first occurrence of deep-sea trawling activities on a pristine sedimentary environment could have triggered sediment instabilities and localized slope failures leading to this sedimentary pulse-event, as has been observed in other trawled submarine canyons of the NW Mediterranean (Paradis et al., 2017, 2018a, 2018b).

The observed increases in sedimentation rates in all canyons were accompanied by an upward siltation since the 1980s (Fig. 2), which is attributed to the effect of grain size winnowing and sorting related to bottom trawling sediment resuspension. After sediment is resuspended by trawling, there is a preferential redeposition of coarser sand fraction on fishing grounds (Martín et al., 2014a; Palanques et al., 2014; Paradis et al., 2021), whereas finer fractions such as silts are advected by ambient currents, depositing in areas farther away from trawling

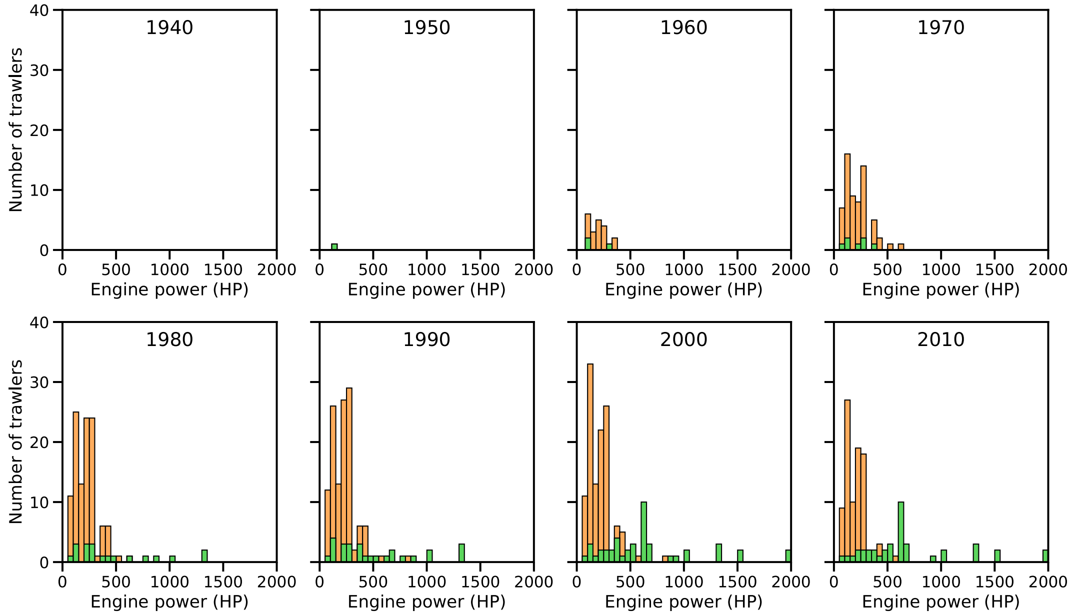

Fig. 4. Decadal distribution of engine power (HP) of bottom trawlers of Palermo (green) and Porticello (orange) from 1940 to 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

grounds (Linders et al., 2018; Paradis et al., 2019). Interestingly, the silt fraction of sediment cores collected in all canyon axes presented an even more prominent siltation in the upper 4 cm of the cores, reaching ~80% (Fig. 2). This greater siltation suggests that these sites could be receiving greater amount of trawling-derived sediment over the last years as a result of the recent modernization of the Palermo bottom trawling fleet in the mid-2000s (Figs. 3, 4). Indeed, the construction of even more powerful bottom trawlers with engine power surpassing 1500 HP would be able to resuspend and transport siltier sediment into submarine canyons.

Overall, the alterations in sedimentation rates caused by bottom trawling fleets in submarine canyons incising the Gulf of Palermo are similar to those observed in the submarine canyons incising the NW Mediterranean (Martín et al., 2008; Puig et al., 2015; Paradis et al., 2017, 2018a, 2018b). This provides further evidence that analogous impacts could be occurring in all trawled submarine canyons in the Mediterranean Sea, where the importance of deep bottom trawling activities has been increasing since the 1960s and 1980s for all reported fishing fleets (Sartor et al., 2011), in agreement with the timeframe of the enhancement of sedimentation rates documented in the canyon axes studied so far.

Considering that bottom trawling has become the most widespread activity greatly impacting European seafloors, a recent European technical report highlights that the alterations in sedimentation rates should be considered when establishing measures to reduce the impacts of this anthropogenic activity (Korpinen et al., 2019). Indeed, several studies have shown that the enhanced sedimentation rates in submarine canyons modify benthic community structures (Pusceddu et al., 2014; Román et al., 2016, 2017), displace benthic burrowing organisms (Tecchio et al., 2013; Puig et al., 2015) and affect the distribution of deep-sea corals within canyons (Lastras et al., 2016; De Leo et al., 2019; Bilan et al., 2020). Moreover, given the high contamination of surficial sediment in the Gulf of Palermo (Tranchina et al., 2008), resuspension by bottom trawling could also remobilize contaminated sediment (Hanebuth et al., 2018), transporting it into the canyon and spreading the spatial influence of industrial contamination. Since the expansion of bottom trawling grounds to deeper areas including submarine canyons has been occurring at a global scale (Norse et al., 2012; Watson and Morato, 2013), further research is needed to determine whether trawled canyons worldwide are affected by an enhanced anthropogenic sedimentation, and evaluate the potential ecological consequences that can be derived from this phenomenon.

5. Conclusion

The 1980s expansion of bottom trawling fleets in the Gulf of Palermo (southwestern Mediterranean) produced higher sediment fluxes into the local submarine canyons, drastically modifying their natural sedimentary regimes by increasing sediment and silt accumulation since that period. Bottom trawling on the flanks and adjacent open slopes of Eleuterio and Arenella canyons induced the transport of large volumes of sediment into both canyons, leading to an order of magnitude increase in sedimentation rate in their axes. In contrast, high sediment fluxes induced by this activity in Oreto Canyon are combined with recurrent sediment resuspension by trawling along its axis, leading to a lower, albeit significant, seven-fold increase in sedimentation rate. The sediment that is continuously resuspended by bottom trawling along the Oreto Canyon axis is transported farther downcanyon, doubling sedimentation rates in even deeper canyon reaches. This study presents new findings that the alterations in sedimentary regimes by bottom trawlers occur not only in the NW Mediterranean canyons, where it was documented until now, but also in other Mediterranean margins. We highlight that all trawled submarine canyons in the Mediterranean Sea may have been converted into anthropogenic depocenters by the technification of the operating trawling fleets between the 1960s and 1980s, and further research is needed to discern whether similar effects occur in other trawled submarine canyons worldwide.

CRediT authorship contribution statement

Sarah Paradis: Conceptualization, Formal analysis, Visualization, Writing – original draft. **Claudio Lo Iacono:** Conceptualization, Resources, Supervision, Writing – review & editing. **Pere Masqué:** Conceptualization, Resources, Supervision, Writing – review & editing. **Pere Puig:** Conceptualization, Resources, Supervision, Writing – review & editing. **Albert Palanques:** Resources, Writing – review & editing. **Tommaso Russo:** Formal analysis, Writing – review & editing.

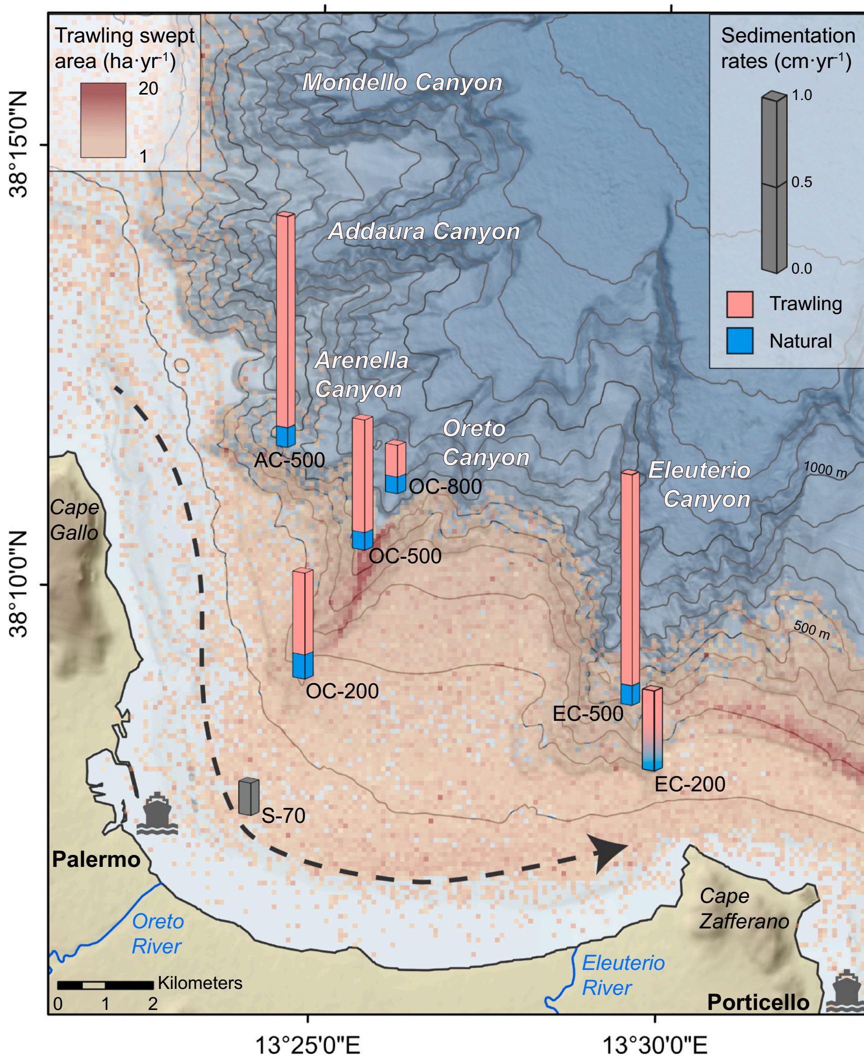

Fig. 5. Sedimentation rates of sediment cores in the Gulf of Palermo, distinguishing between natural (blue) and trawling-derived (red) sedimentation rates in the submarine canyons. Note that since sedimentation rates of EC-200 could be influenced by bottom trawling activities, this bar graph shows a gradual change from natural and trawling-derived colors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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