Development, human impact and habitat distribution in submarine canyons of the Central and Western Mediterranean

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Abstract

We present in this paper different studies on canyon systems, adopting distinct approaches, distinct temporal and spatial scales. Most of our study areas coincide with the NW Sicilian canyons, which present striking differences in their morphologies in response to the Plio-Quaternary tectonic evolution of the northern Sicilian margin. Present-day sedimentary processes have been inferred through the morphometric analyses of bedform fields observed in some the canyons studied, likely controlled by the action of supercritical flows. These active processes could be responsible for enhancing biological activities along canyons. This is also confirmed by an on-going study of the impact of trawling fishery on the morphology and sedimentary environments of the Sicilian margin, where intense deep-sea bottom trawling activities are registered in some of the canyons. Finally, we present the main results of the application of habitat distribution models in the Cap de Creus Canyon (NW Mediterranean), considering them as possible contributions in developing sustainable methods for the management of natural resources. The multidisciplinary and holistic perspective that a rises from these studies suggests that the integration of different approaches should be considered by future scientific investigations looking at submarine canyons as dynamic, interactive natural systems.

1 - Introduction

Submarine canyons are prominent features recognized as complex systems regulating the natural dynamics of continental margins. Canyons play a key role in source to sink sedimentary processes, they drive meso-scale oceanographic circulation, organic carbon redistribution and finally the functioning of ocean ecosystems. Despite their importance, some of the scientific issues regarding the evolutionary and present-day maintenance processes of submarine canyons and their role in maintaining ocean biodiversity are still controversial. This is mainly due to the lack of high-resolution datasets and long-term observations. Moreover, the wide spectrum of geologic, biologic and oceanographic processes occurring along canyons make these complex settings far from being understood and suggest that efforts towards multidisciplinary approaches can lead to a better knowledge of global patterns in canyon dynamics. We present here case studies from the NW Sicilian Canyons (Southern Tyrrhenian) and from the Cap de Creus Canyon (NW Mediterranean) illustrating different although interrelated approaches and scales in the study of submarine canyons. We will present an analysis of long and short term shaping geologic processes contributing to the development of the NW Sicilian Canyons. In addition, we present evidence of trawling fisheries along the NW Sicilian margin which suggests that human activities have potential implications on the alteration of natural landscapes and sedimentary transport processes along canyon systems. Finally, we will highlight the role of the Cap de Creus Canyon in hosting and preserving sensitive habitats such as the cold-water coral communities, demonstrating the need for solid species distribution models in the management of deep-sea natural resources. Datasets used in this work have been collected along the NW Sicilian Margin in 1982 (Department of Industry of the Italian Government), 1996 (CNR- Sicily 96 Cruise), 2001, 2004 (CARG Project) and 2009 (MaGIC Project). Metadata about fishing effort (from VMS) along the Sicilian Margin have been provided by the University of Rome "Tor Vergata". Data from the Cap de Creus Canyon have been collected in 2004 by Fugro N.V., AOA Geophysics and the University of Barcelona.

2 -Development of NW Sicilian Canyons under a complex tectonic setting

2.1 - Geological setting of the NW Sicilian margin

The Sicilian margin corresponds to a young, tectonically active shelf to slope setting linking the Sicilian–Maghrebian Thrust Belt to the Tyrrhenian oceanic realm, developed during the late Neogene–Quaternary time span. This region originated as a consequence of a complex interaction of compressive events, crustal thinning and strike-slip faulting. Late Miocene–Early Pliocene high-angle reverse faults produced structural highs along the margin, giving origin to semi-enclosed intraslope basins (e.g. the Palermo Basin), termed "peri-Tyrrhenian basins" by Selli (1970). These basins were eventually filled with Upper Neogene to Quaternary turbiditic, evaporitic, hemipelagic and volcaniclastic deposits, up to 1200 m thick. In the present-day, the upper plate seismicity of the northern Sicilian margin is defined by compressive focal mechanisms to the west and extensional to strike-slip mechanisms to the east. Inshore and offshore geological data on the northern margin suggest that while the mainland sector is uplifting, the offshore area is presently subsiding, causing differential vertical movements of the margin (subsidence vs uplift).

2.2 - Geomorphology and long-term development of the NW Sicilian canyons

Multi Beam swath bathymetry along the NW Sicilian Margin reveals a dense submarine canyon network, with up to 21 canyons mapped along a distance of 110 km. Sicilian Canyons show striking differences in their morphology and in the sedimentary processes which governed their evolution, despite their close spacing along a continental margin controlled by the same large-scale tectonic, sedimentary and oceanographic processes. Three main canyon typologies can be distinguished in the study area: 1) steep and deeply incised sediment-fed canyons; 2) steep and incised retrograding canyons (some of them being slope confined); 3) gently sloping, sinuous to meandriform sediment-fed canyons (Fig. 1). The first type corresponds to the Eleuterio and Oreto Canyons, in the Gulf of Palermo (Figs. 1,2). The second type corresponds to the retrograding canyons of the Gulf of Palermo (Figs. 1,2). The third type of canyons has been observed in the Gulf of Castellammare (Figs. 1,3),

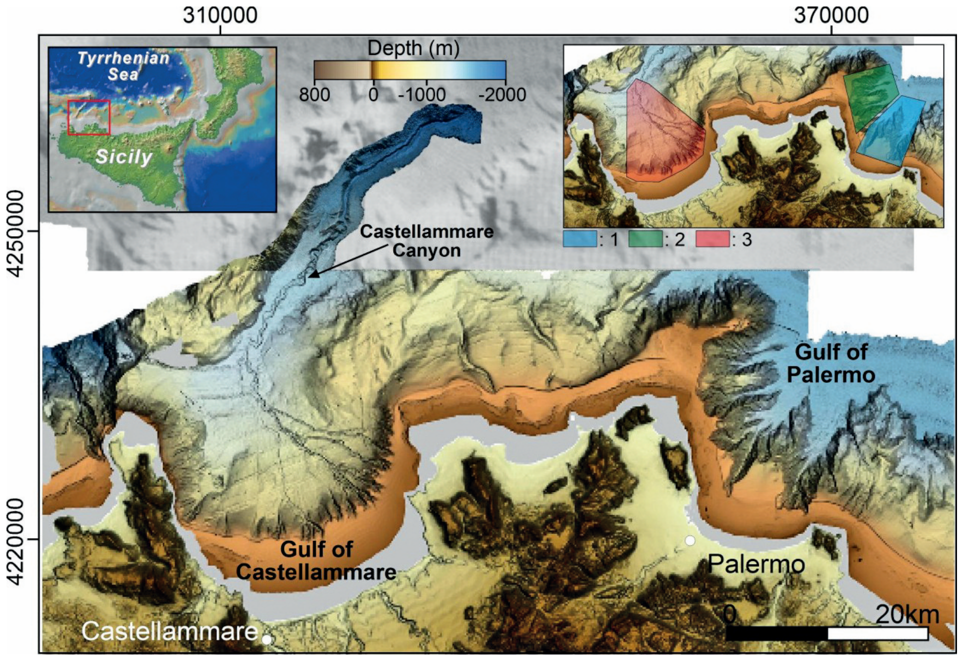

Figure 1. Multi Beam bathymetric model of the NW Sicilian Margin, showing the two main canyon systems described in this paper. The three different colored areas in the top-right inset correspond to the three canyon system types described in the section.

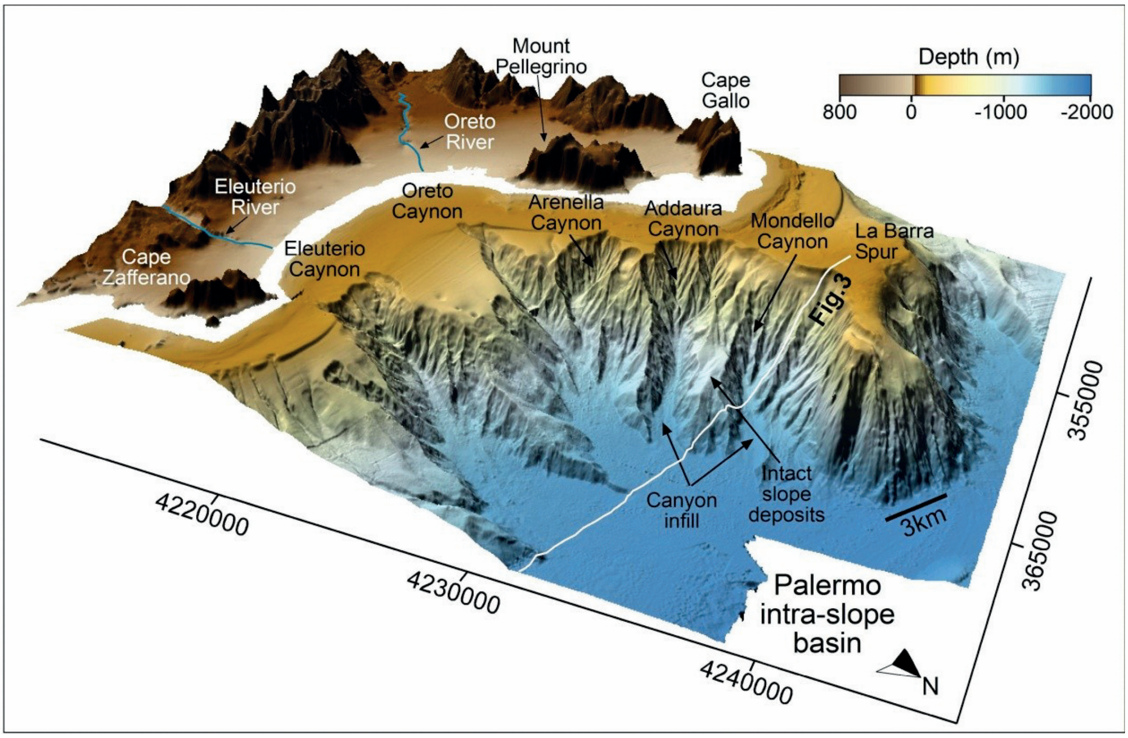

Figure 2. Multi Beam 3D model of the Palermo canyon system.

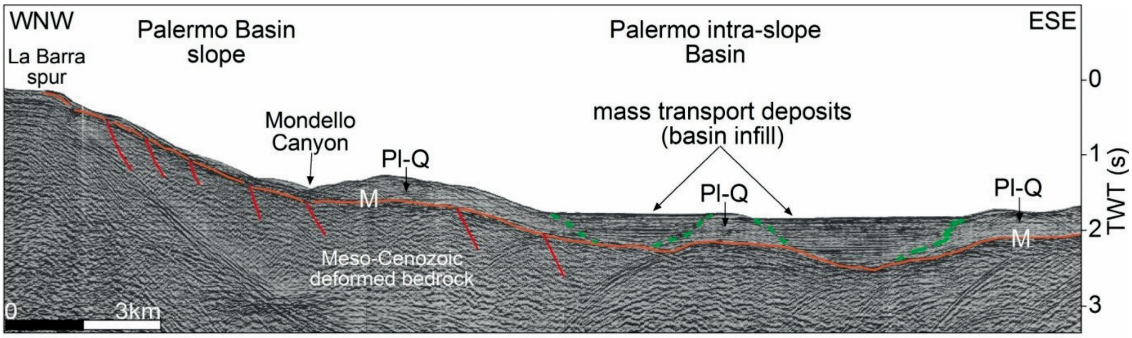

Figure 3. MCS profile crossing the Palermo Basin.

Gulf of Palermo - In the Palermo Basin, the Oreto and Eleuterio Canyons (Type 1) breach the shelf edge at a depth of 110 m and develop towards the Palermo intraslope confined Basin until a depth of 1500 m, likely governed by moderate sedimentary fluvial inputs from the Oreto and Eleuterio Rivers. These canyons display a slightly sinuous shallow reach, followed in the distal branch by a straight path. The Eleuterio Canyon, located in the easternmost sector of the Palermo Gulf, is the largest erosive feature of the Palermo Basin, up to 4500 m wide and about 12 km long (Fig. 2). Contrasting to the sediment-fed Oreto and Eleuterio Canyons, mainly controlled by top-down turbidity currents and hyperpycnal flows, the shelf-indenting Arenella, Addaura Canyons and the slope confined Mondello Canyon are mostly controlled by bottom-up retrograding mechanisms (Fig. 2). These last canyons (Type 2) develop over a steep slope, in a sector where the continental shelf displays its minimum width of 3.5 km, bounded inshore by the Meso-Cenozoic carbonate promontory Mount Pellegrino (Fig. 2). These canyons, with steep gradients from 7 to 13, potentially evolved following a retrogressive migration of stacked landslides, actually coalescing along the upper slope (Fig. 2). Multi Channel Seismic records show that the Plio-Quaternary succession developed over low frequency reflectors with variable amplitude constituting the Meso-Cenozoic carbonate units, outcropping onland and downthrown by high angle normal faults towards the Palermo intra-slope Basin. The Plio-Quaternary clastic succession, several hundred meters thick, is deeply cut by the Palermo submarine canyons (Fig. 2). The steep gradients of the slope and its convex-up geometry likely favoured the development of landslides along the lower slope, carving the Plio-Quaternary succession and giving origin to the canyons retrograding towards the shelf-margin. Seismic records crossing the Palermo Basin reveal the presence of an undisturbed Plio-Quaternary succession which has been deeply eroded and eventually infilled by onlapping sub-horizontal deposits, up to 0.7s thick, suggesting a polycyclic development, with alternate depositional and erosive phases related to the margin and canyon evolution (Fig. 3). Deep and old incisions along the foot of the slope were likely buried progressively by unconsolidated mass-wasting deposits resulting from the subsequent bottom–up migration of the Palermo Canyons. The lack of incisions deeper than 1500 m (Fig. 2) must be related to the structural barrier confining the Palermo intra-slope Basin, hampering the action of sediment transport processes along deeper depths and favouring a depositional setting similar to a "cul-de-sac". The retrograding evolution of the Palermo Canyons could be driven by the active tectonics described along the northern Sicilian margin, with tiling movements that may induce a progressive over-steepening of the slope and consequent headward erosion towards shallower and stable slope sectors. A relevant downslope increase in seafloor inclination is evident along the Palermo slope in a depth range of 200-400 m, where deeper sectors show an over-critical slope exceeding 12°. The high inclination would favour slope instabilities evolving backward towards shallow depths, over a less steep slope. This general model has been reported in other tectonically active margins of the Mediterranean, such as the north-eastern Cretan margin.

Gulf of Castellammare – The submarine canyons of the Gulf of Castellammare (Type 3) are clustered in the south-eastern sector of the slope (Fig. 4). In this region, contrasting to the canyon types of the Gulf of Palermo, a number of gently sloping narrow meandriform canyons and less incised gullies breach the shelf margin and extend landward in small and narrowing headscarps (Fig. 4). These canyons are mainly dominated by strong fluvial inputs and develop over a less inclined substrate. The Castellammare Canyon (Fig. 4) is the major incision of the Gulf and reaches maximum depth at around 2500 m, connecting with the deep-sea basin at the foot of the Ustica volcanic edifice. Seismic reflection profiles collected along the upper slope reveal a dense network of buried valleys and vertically stacked channel-levee systems throughout most of the Plio-Pleistocene succession over a less inclined pre-Pliocene substrate. Top-down turbidity flows flushing through submarine canyons seem to be the primary mechanism responsible for building the Castellammare shelf to slope system and for nourishing the basin since the upper Pliocene until the present day. Turbidity currents related to river sediment discharges promoted the creation of a complex sedimentary system, developed with meandering channels, tributaries and gullies. At the depth of 1100 m, the course of the Castellamare Canyon appears to be heavily influenced by the major morpho-structural features of the non-confined intra-slope Castellammare Basin. Along this sector the convex-up longitudinal profile suggests a tectonic uplift active during the Quaternary, in accordance with previous observations, which produced a V profile cross section and an incision of the Castellamare Canyon of up to 94 m at a depth of 1300 m. Similar neo-tectonic related features have been observed in active convergent margins, such as the South Colombian and New Zealand–Hikurangi margins.

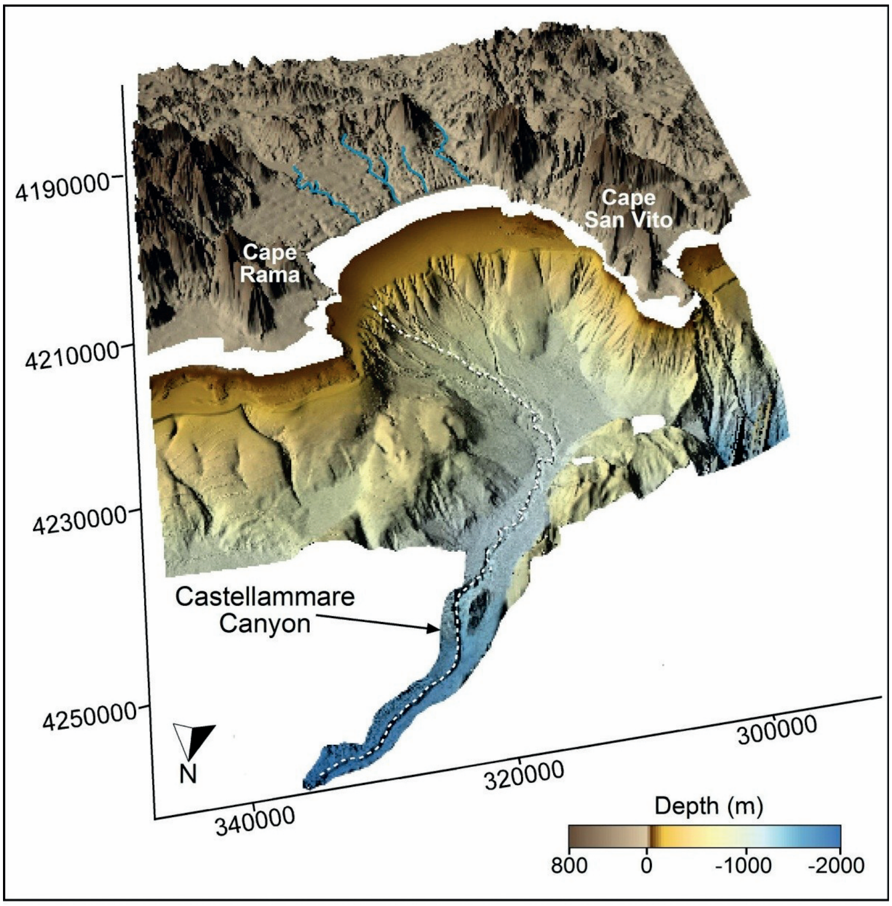

Figure 4. Multi Beam 3D model of the Castellammare Canyon.

2.3 - Present-day sedimentary processes along the NW Sicilian canyons

NW Sicilian canyons located along the easternmost sector of each gulf and in front of the most prominent promontories and capes actually display the deepest incisions. In contrast, the rest of

NW Sicilian canyons generally display a smoother morphology and a reduced axial incision. This observation suggests an enhanced activity of the easternmost submarine canyons in present time, or at least since the beginning of the actual highstand sea-level phase. This could be due to the action of eastward storm-associated longshore currents crossing the outer shelf and steered towards the heads of the easternmost canyons, which may have been also accentuated by the narrowing of the continental shelf and by the actual geometry of the coast. Canyons can trap sporadic downslope gravity flows which may reduce the draping hemipelagic sedimentation along them, although *in situ* measurements are required to confirm this hypothesis. Similar processes have been largely documented in submarine canyons of the NW Mediterranean and Portuguese margin, where almost the totality of resuspended sediments transported across the shelf are flushed along the last canyons of gulfs during extreme winter storm events.

Turbidity current reconstruction based on numerical modelling of cyclic steps

A network of nine gullies breaching the shelf-edge in front of Cape Zafferano, in the Gulf of Palermo, displays a set of crescent-shaped bedforms along their thalweg in a depth range of 125-1050 m (Fig. 5). These crescent-shaped bedforms are here interpreted as cyclic steps, which are upslope-migrating asymmetrical bedforms generally observed along the thalweg of active canyon systems and are controlled by the action of alternating supercritical (erosion) and subcritical (deposition) turbidity currents. Rough estimations of the turbidity currents which generated the cyclic steps can be made using a numerical model for a given range of flow characteristics. The numerical model uses an average grain size, and the stoss and lee side slopes of observed bedforms as input data, running several thousand of simulations for flows combining different discharges, Froude numbers and sediment concentrations. The synthetic bedform lengths and amplitudes predicted by these simulations are eventually compared to the dimensions of the observed cyclic steps, fitting then the most appropriate characteristics of their genetic flow. The cyclic steps of Cape Zafferano displaying a more pronounced and apparently "fresh" morphology are used here as input for the model (Fig. 5). The average characteristics for the bedforms in the deeper section of the gully (700-800 m water depth) are summarised in Table 1. The model calculations indicate that the cyclic steps observed are likely generated by flows around 1 meter thick, with average velocities of 0.8 m/s. The maximum velocities at the tow of the steep lee sides reach values of ~1.5 m/s, whereas in the flatter stoss sides the flow has a maximum thickness of about 2.4 m combined with a minimum velocity of ~0.2 m/s (Fig. 5).

Table 1. Bedform characteristics of profile A-A' in Fig. 5.

Step #	Slope Stoss side [m]	Slope Lee side [-]	Length [m]	Amplitude [m]
Step 1	-0.008	0.164	224	5.8
Step 2	0.026	0.217	198	13.2
Step 3	0.003	0.110	249	3.1
Step 4	-0.038	0.063	286	5.0
Average	-0.004	0.138	239	6.8

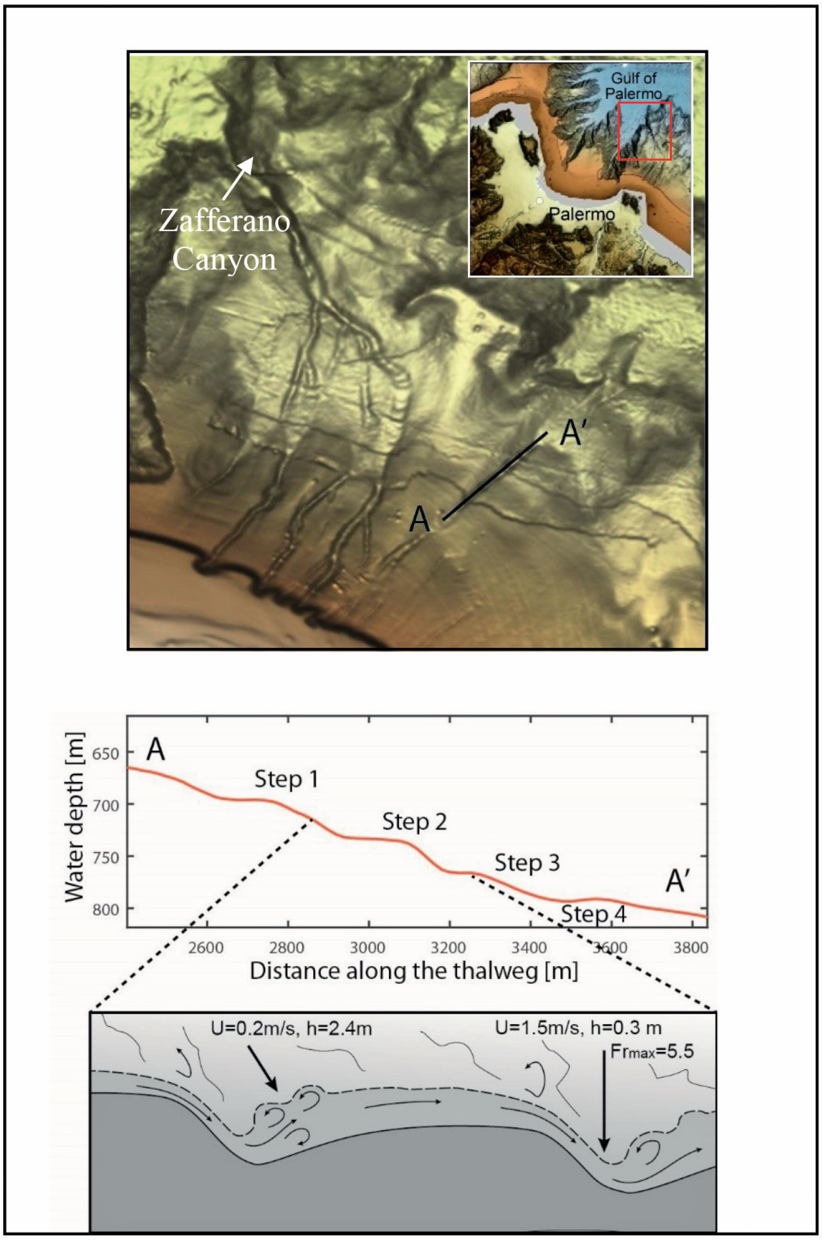

Figure 5. Cyclic steps along the gully network of the Zafferano Canyon. Bathymetric profile crossing the most pronounced cyclic steps and estimation of genetic flows based on numerical modelling.

3 - Anthropogenic impacts along the NW Sicilian Margin: effects of trawling activities on the morphology of submarine canyons

Recent and on-going assessments of human activities along the NW Sicilian Margin are unveiling with unprecedented details the fishing efforts within the region. The accelerated industrial and technological development which occurred in the last decades allowed the trawling fleets to reach deeper depths, while mapping of seafloor morphology is now possible at increasingly higher resolution. The Vessel Monitoring System (VMS) is a satellite-based technology that allows to track the position of fishing vessels with a Length Over All (LOA) larger than 15m. Integrating the Multi Beam bathymetry offshore NW Sicily with the VMS data from trawling activities during the last nine years has recently revealed a potentially strong impact of the deep-sea bottom trawling fisheries at the scale of the entire margin, specifically targeting some of the NW Sicilian canyons. The VMS data related to the activity of the Italian fleet were processed using the R package VMSbase*, a spatial platform based on the methodology described in 27 and 28. According to the acquired VMS data, trawling vessels largely operate along the NW Sicilian margin for depths ranging from 50 m to 700 m, except in areas with rough and abrupt morphologies, such as large rocky outcrops, structural highs or the walls of the steepest canyons. Trawling activities are persistent along the Sicilian canyons which display smoother slopes and a less articulated morphology. One of the most impacted canyons is the Oreto Canyon, in the Gulf of Palermo, with high fishing intensities registered along the thalweg in a depth range of 350-650 m. In the same area, the gully system east of the Oreto Canyon, where cyclic steps were observed, is subject to high trawling efforts, with vessel tracks running parallel to the contour and cutting the gully axes at a depth range of 400-650 m. In this region, some of the gullies display a smoother morphology and reduced incision not easily explained by the action of natural processes, and coinciding with the areas where maximum fishing effort occurs. The impact of trawling thus could have a potentially underestimated implication in altering deep-sea sediment transport pathways. Recent studies showed the cumulative effect of this persistent anthropogenic activity resulting in noticeable increases in gravity flows and sediment accumulation rates inside canyons. Moreover, observations from the NW Mediterranean demonstrated that trawling activities are able to deeply modify canyon landscapes through a constant removal of sediments from fishing grounds, smoothing and reducing the complexity of canyon flanks. Trawling activities can clearly alter benthic habitats on which fish and other marine organisms rely, strongly impacting epibenthic and infaunal abundance and diversity, confirming trawling as a major threat to deep seafloor ecosystems at a global scale.

4- Habitat distribution models in the Cap de Creus Canyon (NW Mediterranean). Contributions for science-based management of natural resources

The persistence of fishing activities along submarine canyons during the last decades suggests that canyons may funnel organic-rich flows potentially increasing the abundance of commercially important demersal fish stocks. Submarine canyons are increasingly described as particularly suitable habitats for listed Vulnerable Marine Ecosystems (VMEs) such as cold-water coral (CWC) reefs, coral gardens and sponge dominated communities, owing to their favourable environmental conditions provided by complex oceanographic and geochemical regimes. Understanding the role of submarine canyons in regulating ocean biodiversity is then of primary importance for the management of natural resources. Predictive habitat modelling has shown great promise improving our understanding of the spatial distribution of benthic habitats. These models are based on complex non-linear statistics, and offer a way to extrapolate limited, point-based information to produce full coverage habitat maps, describing biological distributions and spatial variations over a range of scales. The application of predictive models along the Cap de Creus Canyon (NW Mediterranean) has shown the high-resolution spatial distribution of 3 CWC species (*Madrepora oculata*, *Lophelia pertusa*, *Dendrophyllia cornigera*). A probabilistic spatial ensemble has been produced by merging the outcomes of three predictive approaches, providing a robust prediction for the three species (Fig. 6). According to the models, CWCs are most likely to be found on the medium to steeply sloping, rough walls of the southern flank of the canyon (Fig. 6), aligning with the known CWC ecology acquired from previous studies in the area. Indeed since the Cap de Creus canyon is the last of several canyons cutting the continental shelf of the Gulf of Lion, fast sediment discharges and high-organic material flushes to the deep-sea have been observed mainly through its thalweg and its southern flank.

Based on our experience, we recognize that habitat and species distribution models have intrinsic limitations related to the complexity associated with natural environment dynamics, especially along submarine canyons, which are geologic features subject to variable and sometimes contrasting sedimentary, oceanographic and biogeochemical regimes. On top of that, modellers need to cope with the frequent lack of solid and comprehensive datasets and specific sampling designs, especially in deep-sea settings. Despite these limits, predictive models remain a way forward in describing the spatial distribution of specific sensitive habitats, showing a strong potential as an objective approach for the planning and management of renewable natural resources along submarine canyons.

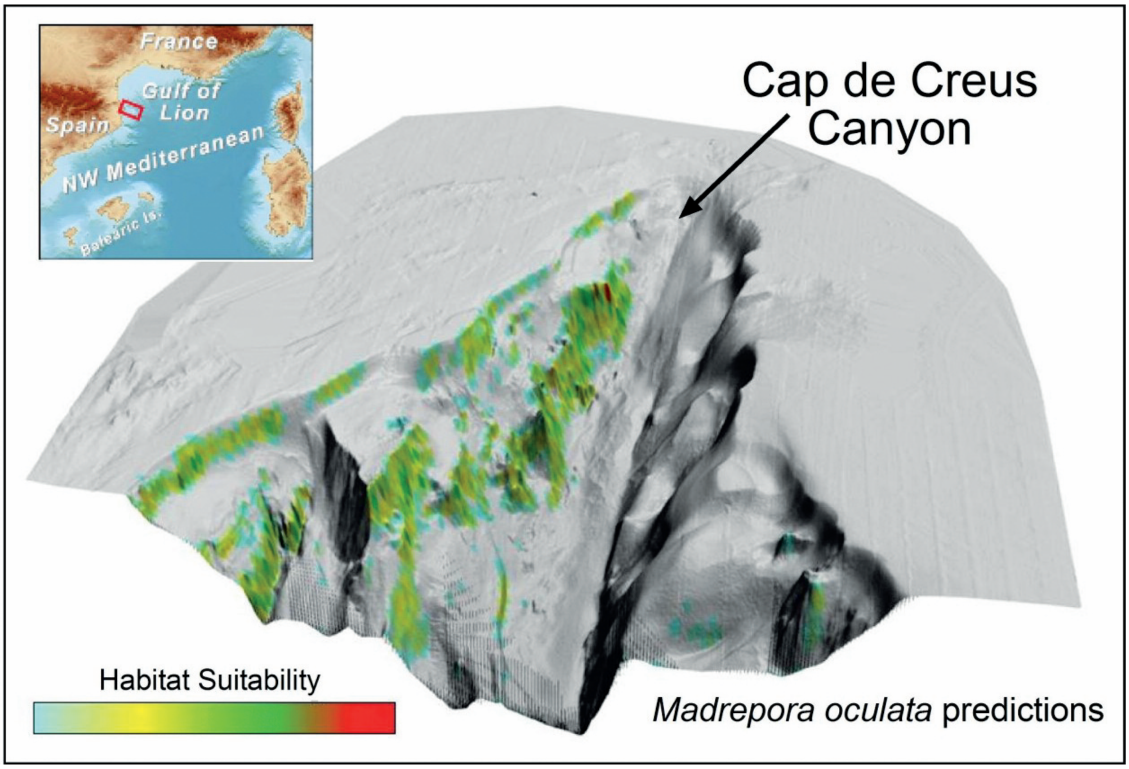

Figure 6. Predictive ensemble map (50 m resolution) for *Madrepora oculata* distribution in the Cap de Creus Canyon.

5 - Multidisciplinary research efforts in the study of submarine canyons

In our work we aimed to describe a range of natural and human processes along submarine canyons which, despite acting at different temporal and spatial scales, are tightly interconnected. Long-term tectonic and sedimentary processes since the late-Pliocene to the present have driven the actual configurations of NW Sicilian canyons (Fig. 1). Although located a few km apart along the same continental margin, the local differences in the structural settings and fluvial inputs of the Castellammare and Palermo Basins are mainly responsible for the variability in canyon morphologies, and possibly in the main sedimentary and oceanographic processes associated to them. For example, shelf-incising canyons likely intercept the organic-matter-rich sediments transported along the shelf zone and are more prone than the slope confined retrograding canyons to enhance sedimentary, oceanographic and geochemical processes. Present-day observations describe retrograding canyons confined to the upper slope as inactive features, sporadically reactivated by bottom currents and internal waves in settings with moderate to strong hydrodynamics. The sedimentary and oceanographic activity sometimes observed in canyons can lead to a strong biological productivity. This is reflected in the on-going analysis of the fishing effort along the NW Sicilian Margin, where some of the mapped canyons are subject to intense trawling activities, confirming that human impact is an additional disturbance process along canyons. Finally, the development of solid spatial predictive analyses, taking into account natural and human processes, is increasingly required to develop feasible methods for planning future sustainable management of canyon resources. However, we are still far from producing a comprehensive understanding of canyon evolutionary mechanisms or from fully understanding the relationships between sedimentary and biological activities along them. Moreover, too few case studies are currently available on the impact of bottom trawling on canyon dynamics. It is suggested that only through more multidisciplinary and integrated research efforts we can gain a comprehensive understanding of canyon systems as a whole.

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