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Submarine canyon dynamics in the Mediterranean and tributary seas - An integrated geological, oceanographic and biological perspective

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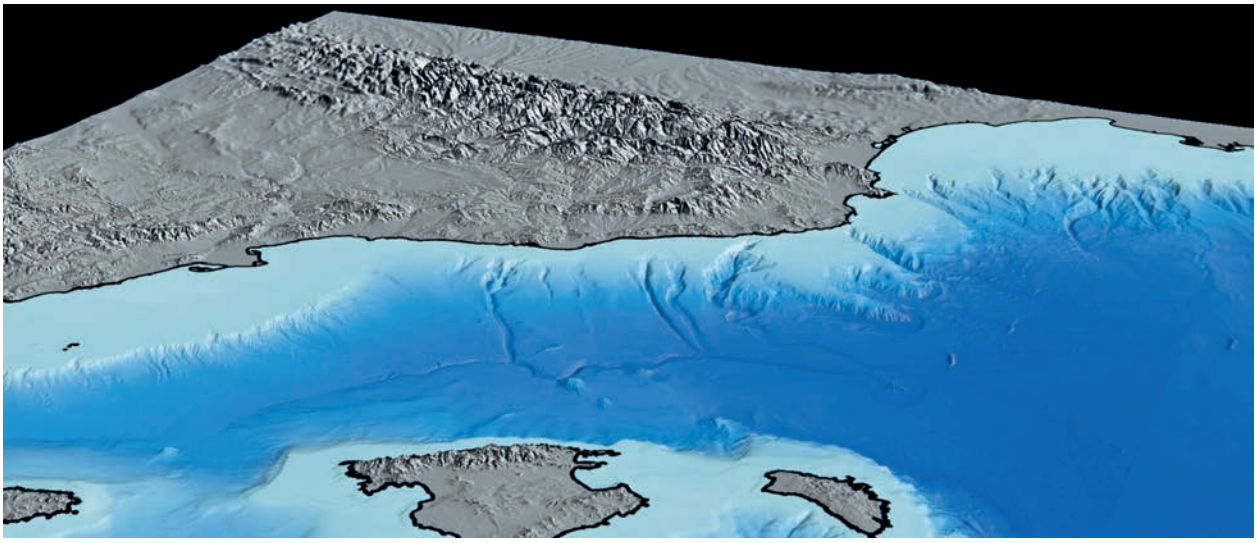

CIESM - The Mediterranean Science Commission

Submarine canyon dynamics

EXECUTIVE SUMMARY [1]

This synthesis, sketched during the course of the workshop discussions, was developed and consolidated in the months thereafter thanks to further inputs, assembled by Silvia Ceramicola, that were received from the meeting participants. The editor, Frederic Briand, reviewed and edited the entire Monograph, with special attention to this opening chapter where his correspondence with Peter Harris, Pere Puig, Namik Çağatay, Marie-Claire Fabri and David Amblas was particularly useful. His gratitude is extended to Valerie Gollino for attending to the physical production of the Monograph under tighter deadlines than usual.

1. INTRODUCTION

The 47th CIESM Research Workshop gathered 16 invited researchers from nine countries and from distinct scientific disciplines to address in a brainstorming format questions related to the formation, evolution, geo-hazard potential and vulnerability of the submarine canyons of the Mediterranean Sea, Black Sea and Marmara Sea which altogether are close to one thousand in number. Our overall objective was to analyze canyons occurring in different geological and climatic settings (active and passive margins, starved and depositional sedimentary environments, regions affected by intensive bottom currents, fault activity, etc.), so as to gain a better understanding of their activity in space and time.

Discussing submarine canyon dynamics through a multidisciplinary approach allowed us to identify both advances in knowledge and remaining gaps concerning the controlling factors underlying the formation, development, ecological functioning and vulnerability of canyons at various time scales. As a result, we identified a number of recommendations for future research and actions that the interested reader will discover in this synthetic chapter, drafted as a collective effort in the months following our meeting. The subsequent chapters, each written by a workshop participant, detail the specificities and dynamics of submarine canyons within and beyond the Mediterranean domain.

Submarine canyons occur worldwide on both passive and active continental margins as single features or arranged in hierarchic systems that may or may not be (a) river-associated, (b) shelf- or slope incising and (c) slope-confined or blind. They evolve over geological timescales and provide important connections from coastal areas to the deep ocean basins (Shepard and Dill 1966). Canyon systems may generate geo-hazards both for coastal infrastructure (harbors, coastal roads and railways, etc.), due to the retrogressive slope failure (mass wasting) of their heads, and to

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[1] to be cited as:
Ceramicola S., Amaro T., Amblas D., Çağatay N., Carniel S., Chiocci F.L., Fabri M.C., Gamberi F., Harris P., Lo Iacono C., Jipa D., Kontoyiannis H., Krastel S., Mascle J., Puig P., Vázquez J.T. and F. Briand. 2015. Submarine canyon dynamics - Executive Summary. pp. 7 - 20 In CIESM Monograph 47 [F. Briand ed.] Submarine canyon dynamics in the Mediterranean and tributary seas - An integrated geological, oceanographic and biological perspective, 232 p. CIESM Publisher, Monaco.

offshore structures such as pipelines, communication cables, etc. (see Canals *et al.* 2006; Piper and Normark 2009; Puig *et al.* 2014). Canyons are often characterized by specific local circulation and surface productivity waters; they exhibit higher particle fluxes and higher sediment accumulation rates than their surrounding open-slope areas, representing important habitats for benthic ecosystems (Vetter and Dayton 1999). Additionally, as submarine canyons act as major off-shelf conduits, they contain the highest density of marine litter in the oceans (CIESM 2014; Pham *et al.* 2014). Thus, a correct understanding of their dynamics and hazard potential is essential to identify and protect vulnerable marine settings.

2. SUBMARINE CANYONS: IMPORTANCE, TERMINOLOGY AND SCALE

2.1 Importance

Early Interest in the evolution, occurrence and distribution of canyons in the World Ocean was initially driven by the need to lay cables and pipelines across the seafloor, to support naval submarine operations, to understand the geological evolution of continental margins as well as the oceanographic and biological processes associated with such features (Heezen *et al.* 1964; Shepard and Dill 1966; Piper 2005). In addition, depositional submarine fans may be found at the down-slope terminus of canyons together with their often extensive fan valley complexes which have been studied in detail as analogues for ancient deposits of economic significance for oil and gas exploration (e.g., Walker 1992; Clark *et al.* 1992).

Oceanographic processes such as internal waves, coastally-trapped waves, the modification (e.g., bathymetric steering) of outer-shelf, and upper-slope geostrophic currents cause the mixing of canyon waters and upwelling of cold, nutrient-rich waters to the sea surface (Hickey 1995; Sobarzo *et al.* 2001; Langone *et al.* 2015). For example, ocean mixing rates inside Monterey Canyon are as much as 1,000 times greater than rates measured in the open ocean (Carter and Gregg, 2002). Canyons that incise the continental shelf have also been implicated in the local amplification of tsunami at the adjacent coastline (Matsuyama *et al.* 1999; Ioualalen *et al.* 2007). The upwelling and mixing associated with canyons enhance local primary productivity and the effects extend up the food chain to include birds and mammals. As a result, commercially important pelagic and demersal fisheries, as well as cetacean feeding grounds (e.g. Rennie *et al.* 2009), are commonly located at the heads of submarine canyons (Hooker *et al.* 1999).

Recent interest has focused on benthic habitats associated with submarine canyons, particularly the heads of shelf-incising canyons that are characterised by steep (vertical to overhanging) bedrock exposures where biologically diverse communities may settle (see Cooper *et al.* 1987; Brodeur 2001; Orejas *et al.* 2009; De Mol *et al.* 2010; Huvenne *et al.* 2012; Yoklavich *et al.* 2012). Submarine canyons that extend across the continental shelf and approach the coast are known to intercept organic-matter-rich-sediments that are transported along the inner shelf zone (e.g. Shepard 1963; Martín *et al.* 2007, 2011; Piper and Normark 2009; Walsh and Nittrouer 2009; Amaro *et al.* 2010, 2015; Cunha *et al.* 2011). It is such a process that causes organic rich material to be supplied to the head of Scripps Canyon and transported down-slope, where it provides nourishment for a diverse and abundant macrofauna (Vetter and Dayton 1998, 1999; De Leo *et al.* 2010). This also explains why seagrass was found at 3,400 m water depth (Gage *et al.* 1995) at the base of Setubal Canyon off Portugal. Canyons that do not have a significant landward extension would presumably not intercept littoral sediments and would not be expected to contain such a rich biodiversity.

2.2 Terminology and scale

Shepard (1963, 1981), in his pioneering morphogenetic classification, recognised that submarine canyons may have several origins and restricted his definition to “steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons”. This definition therefore excludes other seafloor valleys such as delta-front troughs (located on the prograding slope of large deltas); fan valleys (the abyssal, seaward continuation of submarine canyons, some of which are remarkably long); slope gullies (incised into prograding slope sediments); fault valleys (structural-related, trough-shaped valleys, generally with broad floors); shelf valleys (incised into the shelf by rivers during sea level low stands, generally less than 120 m deep); and glacial troughs (incised into the continental shelf by glacial erosion during sea level low stands, generally U-shaped in profile and having a raised sill at their seaward terminus). 'Box' canyons have been described as characterised by amphitheatre-shaped heads, steep and high valley walls, constant valley width, flat floors and low drainage densities (Paull *et al.* 1990; Robb 1990). They are the offshore analogue of morphologies observed on land (Robb 1990), in desert landscapes, on Earth and on Mars (Malin and Carr 1999).

Submarine canyons are generally composed of three sections: 1) a canyon head, cutting the upper part of the slope or incising the shelf edge; 2) a middle canyon, generally incising the continental slope, with or without tributary branches; and 3) a canyon mouth debouching at abyssal depths often into basin areas. The heads of some submarine canyons terminate on the slope, making so-called "blind" or "headless" canyons. The largest canyons, however, commonly incise into the continental shelf and may even continue as shelf valleys that have a direct connection to modern terrestrial fluvial systems. Analysing canyon morphometry can reveal important information concerning their evolution and relative maturity. Canyon thalwegs can be rectilinear or sinuous, and the long profile can be concave or convex in shape, with steps or knick points (Mitchell 2004). The mean depth of canyon incision in Mediterranean canyons is about 1,600 m, which is small compared with global averages (Harris *et al.* 2014).

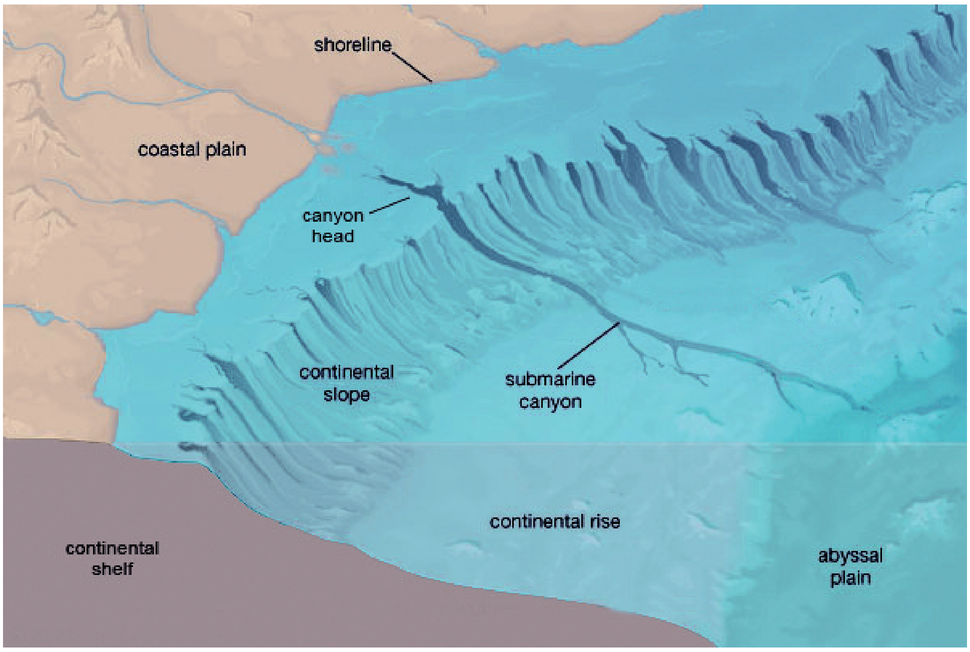

Figure 1. Schematic presentation of a submarine canyon (adapted from Encyclopaedia Britannica 2010).

Regarding the dimensions of submarine valleys (minimum length or depth range), Harris and Whiteway (2011) specified in their classification of "large" canyons that canyon features had to span a minimum of 1,000 m depth range (canyon features that did not extend over at least 1,000 m were excluded). Furthermore, the width/depth ratio (incision) of the canyon was required to be less than 150:1 and canyon incision had to exceed 100 m – features incised less than 100 m were excluded. It is understood that these size limits are arbitrary and are wholly dependent upon the resolution of the bathymetric data used to map canyons.

3. SUBMARINE CANYONS OF THE MEDITERRANEAN, BLACK AND MARMARA SEAS

3.1 Mediterranean Sea

The Mediterranean Sea is characterized by some remarkably young canyons (Pliocene-Quaternary), while others are much older, conditioned by the km-scale lowering of sea levels during the Messinian salinity crisis ca. 5.5 Ma (i.e., Gulf of Lion and Liguria margin). Some canyons formed on active margins after the Messinian event such as the canyons incising the Ionian Calabrian margin (Coste 2014; Ceramicola *et al.* 2014). In comparison to their oceanic counterparts, canyons in the Mediterranean Sea have been described as more closely spaced (14.9 km), more dendritic (12.9 limbs per 100,000 km^2), among the most steep (mean slope of 6.5^o), shorter (mean length of 26.5 km) and with a smaller depth range (1,613 m) than canyons that occur in other regions of the world (Harris and Whiteway 2011).

The inventory of Mediterranean submarine canyons is far from complete as it largely depends on the resolution of the available seafloor data (Harris and Whiteway 2011; Würtz 2012; Harris *et al.* 2014). So far more than 800 examples of *large* canyon systems have been counted by Harris *et al.* (2014) for the Mediterranean Sea using Shuttle Radar Topography Mapping (SRTM30_PLUS) 30-arc second database (Becker *et al.* 2009). In recent years national and international programmes have funded acquisitions of new higher-resolution morphological data (e.g., MAGIC Program for Italian continental margins), allowing canyon systems never observed before to be identified (see Trincardi *et al.* 2014; Langone *et al.* 2015). It must be noted that for the European sector of the Mediterranean Sea the seafloor data compilation is quite advanced and is made available to the scientific community via European digital databases (i.e., EMODNET), while the quality and resolution of available data are much lower for the African sector. We have little doubt that the number of canyons incising the Mediterranean Sea will likely turn out to be much higher than what it has been estimated so far.

The most important and widespread canyon systems have been located on the western continental slopes of the Mediterranean Sea (see Fig. 2 below). In this Monograph the interested reader will find detailed examples from the Alboran Sea (Vázquez *et al.* this volume), Catalan-Balearic margins and Gulf of Lion (Amblas *et al.* this volume), Ligurian margin (Mascle *et al.* this volume), the Tyrrhenian Sea (Gamberi this volume), the Calabrian (Ceramicola *et al.* this volume), the Sicilian margin (Lo Iacono *et al.* this volume) and references therein. The western basins of the Mediterranean Sea are older (25Ma) and have formed as a consequence of tectonic rifting, whereas the younger eastern margins are associated with subduction of the African plate under the European plate (Mediterranean ridge). Most of the Western Mediterranean canyons are partly superimposed on former sub-aerial/submarine valleys created during Messinian times (roughly between 6 and 5Ma) when the sea level dropped drastically, perhaps by 1,200 to 1,500 m (see CIESM 2007).

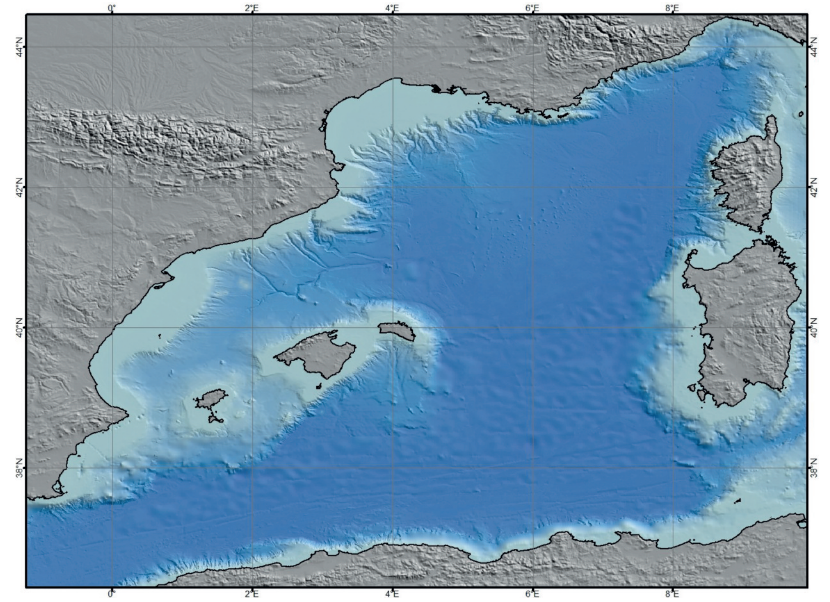

Figure 2. The highest density of Mediterranean submarine canyons is found in the northwestern Mediterranean depicted here. Composite image based on data sets from the MediMap Group (2005) and GEBCO Digital Atlas (IOC, IHO and BODC 2003).

The Italian Adriatic margin is a portion of foredeep almost filled by debris produced by dismantling of the Alps, Apennines and Dinarides, and shows canyons only in its southernmost part (see Carniel *et al.* this volume); the Ionian Sea is a relict, old oceanic (and therefore deep) crust that was destroyed by the collision between Africa and Europe and its margin is carved by a countless number of canyons; the Tyrrhenian Mio-Pliocene back-arc basin shows deep, long but solitary canyons to the west (Sardinia), to the East (Campania), to the North (Liguria) and to the south (Sicily and Calabria); finally the western Mediterranean Oligo-Miocene back arc basin shows diffuse canyons and channels carving the western Sardinia margin (Chiocci this volume).

In the younger continental margins of the eastern Mediterranean Sea, originated by collision and subduction tectonics, canyon systems developed less intensively: only Cyrenaica and Western Egypt continental slopes show significant canyon networks (see Mascle *et al.* this volume).

3.2. Black Sea

Our Workshop allowed the first general review of the Black Sea canyons (Popescu *et al.*, this volume) for which there is relatively little information. While the Danube (also called Viteaz) Canyon has been more thoroughly and more systematically investigated than others (see for example Popescu 2002; Lericolais *et al.* 2002; Popescu *et al.* 2004), our discussions were enriched by recent significant data on other Black Sea canyons (e.g. Pasynkova 2013; Gulin *et al.* 2013).

The characteristics of Black Sea canyons strongly depend on the relief of the coasts they are associated with. On the basis of their dynamics, two main categories of canyons can be considered: active and inactive (inoperative). The active canyons face the mountainous Black Sea coasts (Crimean, Caucasian and Pontic mountains) in zones with narrow shelves. They deeply incise the shelf, have steep walls, high gradient thalwegs and receive coarse-grained sedimentary load from closely discharging rivers. In this category, the submarine canyons located close to the Caucasian coast are the best known, because of their pronounced societal relevance. In the Caucasus a close relationship exists between the main submarine canyons (Bzyb, Kodori, Inguri, Rioni, Supsaand Chorokhi/Çoruh) and the rivers discharging near the respective canyon heads. The canyons are channelling down-slope, to the deep marine environment, transporting an important amount of the Caucasian rivers sediment. This leads to intensified shoreline erosion and affects human settlements.

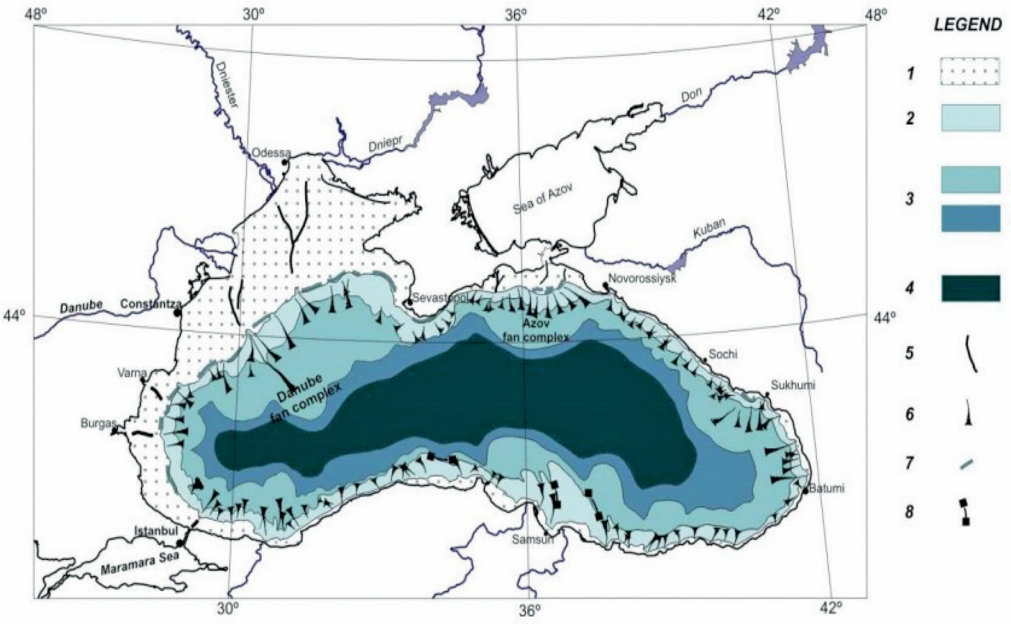

Figure 3. Geomorphologic zoning of Black Sea (from Popescu *et al.* this volume). Color coding and symbols: 1. continental shelf; 2. continental slope; 3. basin apron; 3 a. deep sea fan complexes; 3 b. lower apron; 4. deep sea (abyssal) plain; 5. paleo-channels on the continental shelf filled up with Holocene and recent fine grained sediments; 6. main submarine valleys-canyons; 7. paleo-cliffs near the shelf break; 8. fracture zones expressed in the bottom morphology.

The largest inactive canyons of the Black Sea (Danube and Dnieper canyons) are located in the north-western and western sectors, characterized by low, accumulative coasts and extensive shelf.

Black Sea canyons clearly show the influence exerted by alternating episodes of glaciation and deglaciation in the Quaternary, which seem to have controlled their evolution. In this respect the Danube and Dnieper canyons are models for presently inactive canyons located far away from the coastline, and with no apparent connection to rivers.

3.3. Sea of Marmara

Our Workshop was enriched by the presentation of the first general compilation of bathymetric and seismic data on the submarine canyon systems of the Sea of Marmara (Çağatay *et al.* this volume and references therein). Located on a major dextral continental transform fault boundary, the Sea of Marmara has steep continental slopes (up to 30° slope angle) that are marked with numerous canyons extending into the ~1,250 m-deep strike slip basins. The Marmara canyons are commonly short (1-3 km), except for the the İzmit, North İmralı and Şarköy canyons which range between 30 and 50 km long. The canyons started forming by tectonic and erosional processes mainly during the Plio-Quaternary, with uplift of the basin margins and subsidence of the deep basins. Some of the canyons such as the İzmit and Şarköy canyons occur on faults or fault zones (see Çağatay *et al.* this volume). The evolution of all Marmara canyons, including those that are fault-controlled, was strongly influenced by climatically controlled cyclic sea (lake) level oscillations. The Şarköy and Bosporus canyons are found at the extension of the Çanakkale (Dardanelles) and İstanbul (Bosporus) straits. Their morphology was strongly modified by erosional and depositional processes resulting from the passage of large water masses between the Mediterranean and Black seas. At present, the water exchange through the canyons plays a major role in oxygenation and biological diversity of the Marmara and Black seas basins. On the southern margin the sinuous North İmralı Canyon most probably developed at the shelf extension of the Kocasu River by erosive activity of the turbidity currents. In the Sea of Marmara mass wasting and turbidity current activity in the canyons were more frequent and effective during the periods of low sea level and lacustrine to marine transitions.

4. Factors controlling / affecting canyon formation

4.1 Long term controlling factors

Submarine canyons are erosive features occurring across continental margins that result from the interplay of three major controlling factors: (1) Geodynamic setting and structural controls, (2) Depositional/erosive processes, (3) Sea level changes.

In the long term, canyon formation is strongly controlled by the allogenic processes connected with the geodynamic setting and the structural framework that create continental margins. In the Mediterranean Sea and in the Sea of Marmara, many continental margins are the result of recent extensional processes that have led to steep slope gradient and, often, narrow shelves. During the rifting episodes, various sets of faults were created along the Mediterranean margins that later became preferred sites for canyon formation. Rifting and foundering processes also result in the flooding of sub-aerial valleys that are progressively invaded by the sea and can consequently become submarine canyons. Rift areas are also affected by strong uplift of hinterland areas. Such a geodynamic process is capable of creating high relief coastal ranges often carved by rivers with mountainous regime with high energy flooding events that erode the continental slope, particularly in areas with narrow shelves. In the latter cases (e.g., French Riviera, Calabria, Algeria, Sicily), the terrigenous river inputs are directly transported to canyons and energetic high volume sediment gravity flows can contribute to their deepening.

In the Mediterranean Sea, canyons also develop along compressive continental margins where high gradient continental slopes are maintained by thrust tectonic and folding. Here, structures have in general a trend parallel to the margin, and canyons with alternating slope-parallel and slope-transverse tracts often occur in the crossing of accretionary wedges.

Tectonics, through the activation and deactivation of single faults, also controls canyon evolution on smaller time scales. On active or re-activated margin segments (e.g. Calabria, Algeria, Southern

France, Sea of Marmara) fault evolution can cause renewed slope steepening and canyon excavation and enlargement, canyon abandonment and changes of canyon courses.

The origin of submarine canyons is also intrinsically tied to erosional processes occurring on continental slopes. On open slope regions, different kinds of unconfined gravity flows may use irregularities of the seafloor of any origin (i.e. slide scars, seepage depressions, faults, etc.) as preferential paths, resulting in the self-organisation of gravity driven flows and finally leading to canyon formation. Mass wasting along continental margin plays perhaps the most important role in creating areas where flows are gradually focused and finally confined during the initial phases of canyon excavation. Mass wasting processes are usually enhanced by high sedimentation rates; thus sediment input at margin scale and areas with high sedimentary fluxes can control the timing and location of canyon formation. In addition, mass wasting processes are often characterized by a retrogressive pattern of erosion that can eventually lead to shelf-break indentation favouring the connection between slope erosional areas and sediment input from the coastal areas (Micallef *et al.* 2014). In this way canyons are established as erosional fairways where transport of sediment from the shallow coastal areas to the deep sea is accomplished.

Submarine canyons, as long-life geomorphic elements, are affected by sedimentary processes that are highly variable in time. Following the initial phase of canyon excavation, fluctuations between erosional and depositional regimes will usually take place until a canyon is completely filled and ceases its activity. The evolution of erosional and depositional processes within canyons results from the complex interplay between various controlling factors that act at different temporal and spatial scales. These key parameters, that can be allo- and auto-genic, are summarised in Fig. 4 in relation to their respective duration.

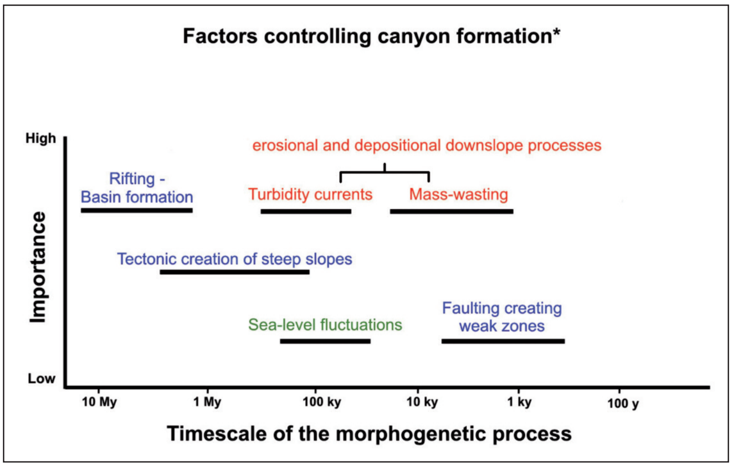

Figure 4. Factors controlling canyon formation over geological time.

Sea level change is of course another important allogenic factor controlling canyon nucleation and evolution. Around the Mediterranean basin, the Messinian event that resulted in a "geologically sudden" sea level drop (estimated on the order of 1.5 km) played a specific and major role in canyon evolution. During the Messinian in fact most of the present day continental slopes were reshaped by sub-aerial erosion, with the upper parts of many present-day canyons acting as rivers.

Sea level variations of smaller amplitude are also particularly relevant to the canyons of the Mediterranean margins. The alternation of glacial and interglacial periods that occurred repeatedly during the last 2.5 Ma is indeed responsible for many of the features of present-day canyons. They cause eustatically-controlled coastal advancement and retreat that are particularly important in driving the energy and the volume of the flows that enter canyon heads. Canyons with heads located at the shelf break, far from the coastline, are at present mainly sediment starved and undergoing a passive infilling phase. However, their morphology can still provide a record of the processes that were active during the past lowstands of sea level, when they were connected to rivers. As the Mediterranean shelf is often quite narrow, many canyon heads remain connected to the coastal area during the present highstand of sea level. In this context, hyperpycnal flows, storm reworking and long-shore current transport can feed sediment to the canyon heads that are then shaped by active processes of erosion, sediment transport and deposition along the canyon axis. Once the submarine canyon is formed, the same factors will keep on controlling its morphological evolution and the canyon will evolve through autogenic process (trending to equilibrium).

Figure 4 summarizes the principal factors controlling submarine canyons formation and evolution over the long-term:

1) Geodynamic setting and structural controls:
    a. Rifting,
    b. Basin formation,
    c. Creation of coastal range,
    d. Presence/absence of continental shelf and coastal plane,
    e. Tectonics (creating steep continental margin slopes),
    f. Faulting (creating weak zones).

2) Depositional/erosional processes:
    a. Self-organization of gravity driven flows: before canyon formation any kind of unconfined gravity flow will use irregularities of the seafloor of any origin (i.e. slides, seepages, faults) as preferential paths, resulting in self-organisation that will end with canyon formation.
    b. Sediment input on margin scale: discharging downslope sediments, sedimentary flux, turbidity currents, confined morphologies.
    c. Mass wasting, retrogressive erosion, high sedimentation rate (favour remobilization and determine how prone is a slope to fail).

3) Sea level changes
    a. Importance of Quaternary sea level fluctuations in submarine canyons formation and evolution.
    b. Messinian event, a specificity of the Mediterranean basin which contributed to reshape most of its continental slopes.

4.2 Natural and human-induced factors affecting canyon dynamics in historical time

Submarine canyons can be affected by natural processes that strongly differ in nature, intensity, frequency and spatial/temporal scale. The short-term processes interesting submarine canyons are meant here as those occurring since the initiation of the present sealevel highstand stage, around 6 kyr BP. They match the actual geologic and oceanographic scenarios of continental margins. They involve oceanographic and sedimentary dynamical processes affecting the physical and chemical setting along canyons (seafloor and/or water column): examples are storms, dense water cascading, internal waves, river floods, turbidity currents, debris flow, canyon flank avalanches and collapses (Puig *et al.* 2014; Tallin *et al.* 2014 and references therein). Human activities, especially deep-sea trawling fisheries developed at industrial scale in the last 50 years (Puig *et al.* 2012; Martín *et al.* 2014) may be included in that category.

The natural and human-induced processes maintaining canyon dynamics do strongly differ in space and time. Large oceanographic events, such as dense shelf water cascading, and extensive turbidity currents, can affect the sedimentary environment and the habitat distribution at the scale of an entire continental margin, developing for thousands of km from the canyon head to the deepest sectors of the depositional channels (Khripounoff *et al.* 2003, 2009; Canals *et al.* 2006; Vangriesheim *et al.* 2009). On the other hand, small-scale mass movements or internal waves and tides can be localized in specific canyon areas, such as canyon heads or flanks (Gardner *et al.* 1989; Xu *et al.* 2010). Defining the minimum scale of processes for which a canyon can be considered a dynamic environment is still an unresolved issue.

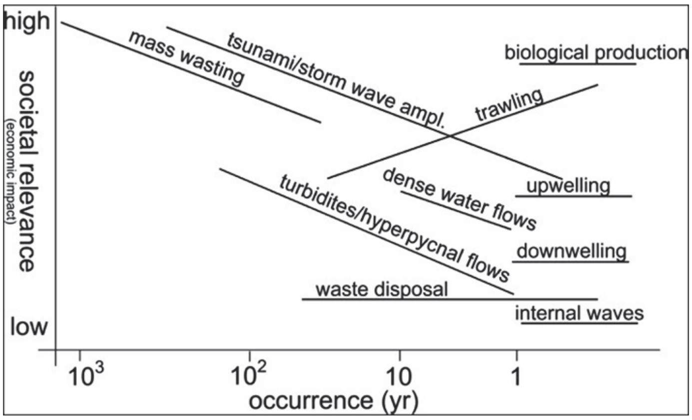

Figure 5. Factors affecting canyon dynamics over the short term.

Important gaps in knowledge have been filled in recent years thanks to comprehensive research, but a solid understanding of canyon dynamics is still lacking. We note, for example, a critical absence of integrated datasets, which would include sedimentary, ecological and oceanographic observations over long time spans. This is due in part to the evident mismatch between the spatial and temporal scales of observations of various scientific groups working on canyon-related topics: they often observe the same natural phenomena under different perspectives.

5 - IMPORTANCE OF SUBMARINE CANYONS TO HUMAN SOCIETIES

5.1 Geo-hazards and mass wasting

Where the canyons deeply incise the continental shelf and develop close to the coast, the prominent headword erosion can provoke collapse of coastal infrastructures (see Casalbore *et al.* 2014; Ceramicola *et al.* 2014a; Migeon *et al.* 2011; Casalbore 2011). Such failures have the capacity to create tsunamis (e.g. Rahiman *et al.* 2007; Zaniboni *et al.* 2014; Macías *et al.* 2015), and may even cut back to the coast and cause direct damage to coastal shore infrastructure or initiate coastal landslides.

Several near-shore areas of the Mediterranean Sea (Alboran, Aegean, Tyrrhenian and Ionian Seas), southern Black Sea and the northern Sea of Marmara are characterized by very narrow shelves and by canyons initiating very close to the coastline. Such settings are especially prone to tsunami generation by failures of canyon heads. Striking examples are the 1977 Gioia Tauro (Italy) and 1979 Nice (France) landslide-tsunamis at canyon head (Casalbore *et al.* 2014; Dan *et al.* 2007). In both cases, the failures were induced by civil engineering activities linked to harbor development and caused waves several meters high that resulted in severe damages and also in human casualties in the latter case (Colantoni *et al.* 1992; Assier-Rzadkiewicz *et al.* 2000). Comprehensive and detailed analyses of submarine canyon heads, including the geotechnical properties of the seafloor and sub-seafloor, are a strict requisite in refining the current geo-hazard assessment models to inform stakeholders with concrete protection measures.

As indicated repeatedly in this volume (e.g., Chiocci; Gamberi), submarine canyons can also capture flash floods and channelize strong turbidity currents, that are able to reach down-canyon velocities >10 m/s with the potential to break pipelines and cables (see Piper *et al.* 1999), now so essential to maintain our lifestyle.

It is widely accepted that mass wasting events do play an important role on canyon initiation and evolution (Micallef *et al.* 2012). Failures at midslope locations followed by upward retrogression may initiate canyon formation (Pratson and Coakley 1996). In addition, canyon flanks become unstable, mainly due to basal erosion produced by gravity flows. This process is the cause of canyon widening, as witnessed by the large number of complex scars and instability features observed on canyon walls.

Such slope sediment failures may also trigger tsunamis. For failures on the open slope, landslides with the following characteristics are usually considered to trigger tsunamis of significant height: (1) shallow-water to intermediate depths (<1,000 m); (2) significant volumes (>2 km^3); (3) stiff cohesive material (e.g., consolidated clay); and (4) rapid initial acceleration of the failed material (Ward 2001). Of course the combination of these factors is crucial in determining the magnitude of the generated waves, given that even a small volume in very shallow water may produce higher waves than a very large volume in deep water. Most failures in canyons are much smaller than the 2 km^3 mentioned above, but failures of canyon heads may occur very close to the coast and in shallow waters.

5.2 Fishing and living resources

The deep submarine canyons and adjacent slopes of the Mediterranean Sea are increasingly impacted by anthropogenic activities such as industrial fishing (Puig *et al.* this volume), litter accumulation and chemical pollution (see CIESM 2014; Canals *et al.* 2013).

Deep-sea organisms are highly sensitive to the arrival of external inputs. Therefore canyons channelling organic matter are sectors of increased biomass and productivity which can exceed that of other deep-sea habitats by orders of magnitude depending on the canyon (Tyler *et al.* 2009; De Leo *et al.* 2010; Vetter *et al.* 2010; Huvenne *et al.* 2011). No pattern in diversity, abundance and biomass is universal because different taxonomic groups show a variety of patterns according to particular environmental conditions at specific depths and localities which may alter biodiversity trends. The general lack of taxonomic resolution in canyon studies does not permit to resolve the controversy on whether canyons are hotspots of biodiversity or not (Cunha *et al.* 2011).

5.3 Trawling damage

Bottom trawlers now reach down to 800 - 900 m water depth regularly, with a limit fixed at 1,000 m in European waters thanks to EU regulations. They have devastating impacts - both biological and physical - on marine ecosystems and have become a major driver of seafloor disturbance by remobilizing and resuspending sediments, furthermore causing major changes in the morphology of continental slopes. This has been extensively documented in La Fonera Canyon - also known as Palamós Canyon, Catalan margin - where a monospecific fishery targeting blue and red shrimp *Aristeus antennatus* has been operative for several decades between 400 and 800 m depth (see Puig *et al.* 2012; Martín *et al.* 2014a and 2014b).

It was found there that bottom-trawling, by continuously stirring the soft sediment on the seabed over the years, led to a reduction of 80% in meiofauna abundance and of 50% in its biodiversity (Pusceddu *et al.* 2014). Deep-sea trawling has become a global threat to seafloor biodiversity and ocean health, causing effects similar to those originated by man-accelerated soil erosion on land. This is a major cause for concern in our region, given the wide spatial distribution of fishing effort in the Mediterranean continental margins, which largely involves bottom-trawls. Enhanced particle fluxes collected by sediment traps and attributed to bottom-trawling have been reported from other sites such as Foix Canyon (Puig and Palanques 1998b), Guadiaro Canyon (Palanques *et al.* 2005) and Blanes Canyon (Lopez-Fernandez *et al.* 2013)

5.4 Marine litter and contaminants

As noted in a previous CIESM Monograph, the Mediterranean is the sea most affected by marine debris in the world. These originate mainly from land-based sources and are greatly enhanced in the summer months by coastal tourists who generate in only one season up to 75% of the annual waste (CIESM 2014). To compound the problem, plastics and microplastics are now ubiquitous in the marine environment, reaching mean densities of more than 100,000/ km^2 in the Mediterranean Sea (Collignon *et al.* 2012). Plastics are not biodegradable, persisting in the environment for thousands of years.

A great variety of marine debris is found in the Mediterranean, from the beaches to the deep-sea floor. Marine litter is mostly composed of plastics (bottles, bags, caps, lost fishing gears), aluminium (cans, pull tabs) and glass (bottles). Litter, especially plastic, is present in all Mediterranean submarine canyons in considerable quantities, especially when the canyon head is located close to the coast (see Fabri *et al.* 2014).

Since submarine canyons act as natural conduit routes and accumulation sites for marine debris and contaminants which they transport from surface waters to the deep-sea, the general trend is an accumulation of litter with increasing depth (Galgani *et al.* 1996; Ramirez-Llodra *et al.* 2013) . A recent review of marine litter distribution in European seas evidenced the highest litter density in submarine canyons and the lowest on continental shelves and on ocean ridges, except on rocky slopes that may retain fishing gears (Pham *et al.* 2014).

Organisms living in canyon environments are exposed to both physical and chemical harm, the latter encompassing persistent organic pollutants (POPs), that include pesticides, herbicides, plastic additives and pharmaceuticals - a cause for serious concern. A recent study (Koenig *et al.* 2013) carried out in Blanes Canyon provided strong evidence that contaminant levels at 900 m depth were higher inside the canyon than on the adjacent slope. Those contaminants were hydrophobic pollutants closely linked to particle deposition and episodic sediment transport events.

6. WHY PROTECT MARINE CANYONS? AND HOW?

Submarine canyons often provide refuge to a number of vulnerable communities (e.g., spawners, cold-water corals) and therefore are the target of intense fisheries. Steep canyon walls (often rocky and cliff-like) located towards the canyon heads are among the most diverse and productive benthic habitats. Cold-water corals can occur here, in patches, reefs or in large mound structures and can be viewed as ecosystem engineers as they often create important habitats for a diverse fauna (Mortensen and Buhl-Mortensen 2005; Post *et al.* 2010; De Mol *et al.* 2010; Huvenne *et al.* 2011). Some of these communities are within areas of intense fisheries and many of these habitats are severely damaged or under threat. For example, trawling activities can trigger the mobilization of surface sediments, making them available for transport towards greater water depths (sediment gravity flows), which can result in changes in sediment accumulation rates, modification of surface sediment properties, reduction of morphological seabed complexity and decreasing epibenthic and infaunal abundance and diversity (Puig *et al.* 2012, and this volume).

The steepest areas of canyon seafloor, comprising “escarpments” (a seafloor gradient exceeding 5° over an area >100 km^2), were mapped by Harris *et al.* (2014) in a global assessment of seafloor geomorphic features. They found overall that 820,960 km^2 of canyon area (i.e. some 18.7%) consist of escarpment. Interestingly, no more than 1% of escarpment areas - potentially the most ecologically valuable canyon areas - are currently protected worldwide.

Marine Protected Areas (MPAs) cover about 4% of the Mediterranean Sea (CIESM 2011a) and the protection offered to submarine canyons by the existing MPA network is negligible.

As noted in a number of reports, for example in Marin and Aguilar (2012), less than 50% of Mediterranean MPAs have management plans, and only 20% appear to have sufficient financial and human resources. A further, major concern is the fact that too few of the Mediterranean submarine canyons enjoy legal protection. As shown in Fig. 6 below, taken from Fabri *et al.* (2014), there are fortunate exceptions like the Lacaze-Duthiers, Pruvost, Bourcart, Couronne, Planier, Cassidaigne and Stoechades canyons which fall ‘under the protection’ of three French MPAs (Parc Marin du Golfe du Lion, Parc National des Calanques, Parc National de Pro-Cros), or the Petit Rhône and Grand Rhône canyons that are covered by a Restricted Fishing Area ... whereas in the same French EEZ other major canyons like Marti, Sète, Saint-Tropez and Var are left without protection.

Further east in the Ligurian Sea, the tripartite 84,000 km^2 Pelagos Marine Mammals Sanctuary was established in 1999 - the outcome of a joint initiative taken by France, Italy and the Principality of Monaco. Designed to secure a major feeding area for western Mediterranean cetaceans, in particular Fin whales (see Hoyt 2005), it does not extend protection to submarine canyons benthic habitats that are impacted by bottom trawl fishing and other stressors. Overall, the protection of hundreds of vulnerable Mediterranean submarine canyon habitats is currently inadequate and in need of urgent attention.

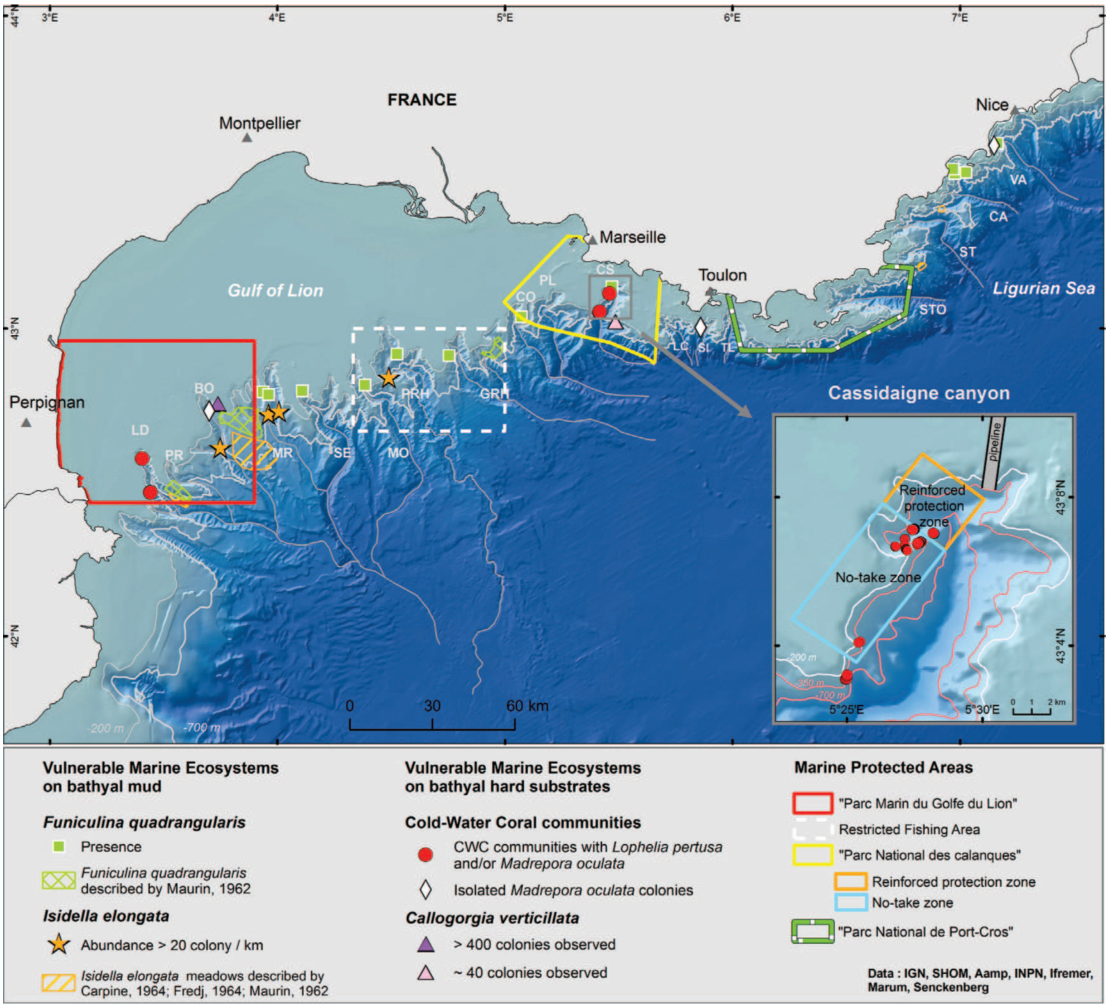

Figure 6. Geographical localisation of the submarine canyons that benefit or not of some protection in the French coastal waters of the Mediterranean Sea. Submarine canyons from West to East: LD: Lacaze-Duthiers, PR: Pruvost, BO: Bourcart (Aude), MR: Marti (Hérault), SE: Sète, MO: Montpellier, PRH: Petit Rhône, GRH: Grand Rhône, CO: Couronne, PL: Planier, CS: Cassidaigne, LC: La Ciotat, SI: Sicié, TL: Toulon, STO: Stoechades, ST: Saint-Tropez (not considered in this study), CA: Cannes, VA: Var. (from Fabri *et al.* 2014)

Yet there are rays of hope for the future: for example in the Palamós canyon off Catalonia, scientists, the Catalonia Fishermen's Association and the Autonomous Government of Catalonia have engaged a collaboration to seek sustainable approaches for the exploitation of the red shrimp *Aristeus antennatus*. Obviously Mediterranean canyons should be managed in a coordinated manner, via an ecosystem-based approach that will require the design of a comprehensive, adequate and representative MPA network. "Comprehensive" means that MPAs must encompass the full range of canyon ecosystems, recognised at an appropriate scale, within and across different bioregions. The MPA network will be "adequate" if it has the required level of reservation to ensure the conservation of ecological viability and integrity of populations, species and communities. This includes replication of ecosystems as essential insurance against loss or damage caused by either natural events or anthropogenic activities outside the control of managers. Finally, the MPA network should contain examples of the full range of different canyon types that are "representative", which means that the canyons that are selected for inclusion in MPAs should reasonably reflect the biotic diversity of the marine ecosystems that exist in the region (Harris 2007).

Marine science can help answer management questions (see Table 1 below) and contribute to the design of a MPA network for the protection and conservation of Mediterranean Sea submarine canyons in several ways. A first step is to identify the different types of canyons that exist and map out, to our best available knowledge, where they occur. Ecological differences between canyons will be driven, to some extent at least, by geological and oceanographic factors such as the lithology of the margin, tectonic setting, canyon age and the physical processes currently acting within them (e.g., the frequency and spatial footprint of slumping and turbidity currents, canyon-induced ocean mixing and upwelling, etc.). From a management perspective, a better understanding is required of the particular vulnerability that canyons have to human impacts. While much of this work can be initiated immediately using existing data sets, further research is needed to adequately address many of the questions posed by managers and authorities (Table 1).

Table 1. Management questions and conservation priorities for Mediterranean submarine canyons.

Management Questions	Research Priorities
What types of canyons exist in the Mediterranean and where are they located?	• Identify the main canyon types that exist in the Mediterranean and their location.
What controls where they are found?	• Understand the geological and physical processes that control Mediterranean canyon distribution to enhance our ability to predict ecological differences between canyon types.
What organisms are found in Mediterranean canyons?	• Characterize Mediterranean canyon biodiversity to better understand, protect and conserve them.• Characterize community structure, including patterns of distribution and abundance.
What ecological roles do Mediterranean canyons play?	• Understand the roles of Mediterranean canyons in supporting various life stages of living marine resources and the processes that regulate these ecosystems.
What are the impacts from natural and anthropogenic threats on Mediterranean canyons?	• Determine the anthropogenic and natural threats to Mediterranean canyons and assess the ecological impacts and their subsequent recovery, if any, from them.

7 – CONCLUSIONS – MAIN GAPS IN KNOWLEDGE AND KEY RECOMMENDATIONS

The Workshop discussions pointed out many gaps in knowledge regarding the driving factors of canyons' formation, their development and ecological functioning, in terms of both long-term (tectonics, sea level changes, sediment dynamics) and short-term processes (flash floods, surge waves, internal waves, up-welling/down-welling, ecosystems functioning, trawling damage, etc.).

Among the top priorities identified by our group:

1) Establish an updated inventory of canyons incising the Mediterranean, Black and Marmara seas and their characteristics, based on geological, physical oceanographic and biological data, in order to improve our global understanding of their distribution and enable regional comparisons between canyon systems.

2) Improve our understanding of the natural drivers controlling canyon functioning (e.g. hydrodynamics, sediment transport, seabed composition, and fluxes of particles), their ecosystems and the current impacts caused by anthropogenic activities.

3) Develop national and international monitoring programmes based on repeated geophysical surveys and long-term biological, chemical and physical oceanographic time-series observations in critical areas for geo-hazard assessment, ecosystems preservation, trawling damage, etc. in order to assess hazards and vulnerabilities and plan a correct management

4) Promote canyon habitat mapping (e.g., multibeam sonar mapping, oceanographic data together with biological sampling, ROVs, AUVs observations, numerical modelling) so as to gain a better understanding of canyon biodiversity and of their environmental status.

5) Connect existing mapping infrastructures and databases at regional and national levels (e.g., EMODNET, EMSO). Add layer dedicated to submarine canyons, their habitats and their vulnerabilities.

6) Assess the evolution and resilience of submarine canyons in the context of climate change scenarios.