ISSN 1726-5886

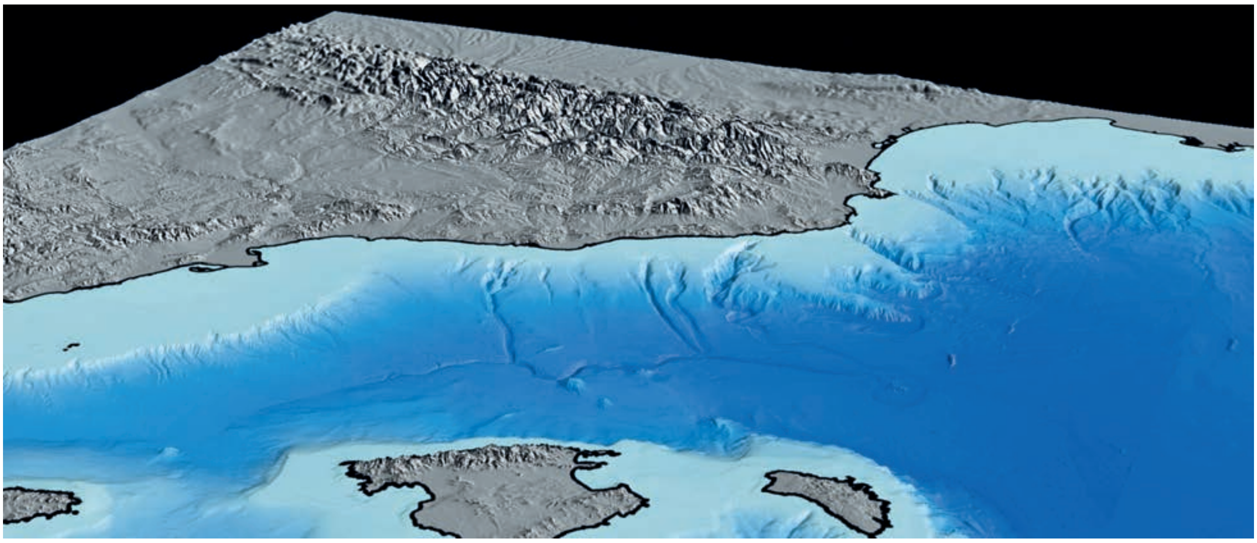
CIESM
WORKSHOP
MONOGRAPHS

47

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

Sorrento (Italy)

15 - 18 April 2015



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

[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).

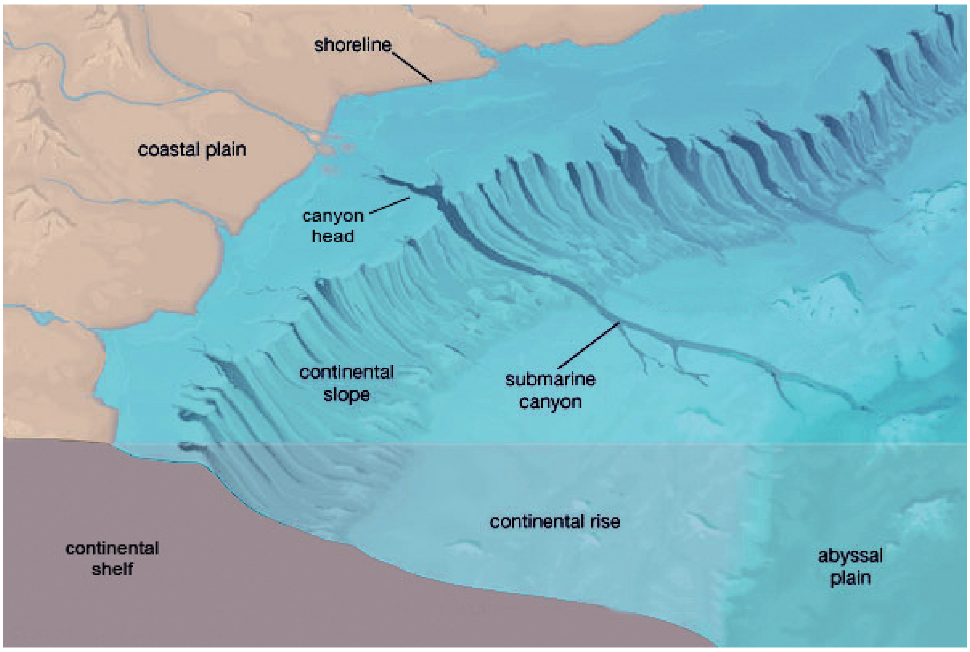


Figure 1. Schematic presentation of a submarine canyon (adapted from Encyclopaedia Britannica 2010).

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).

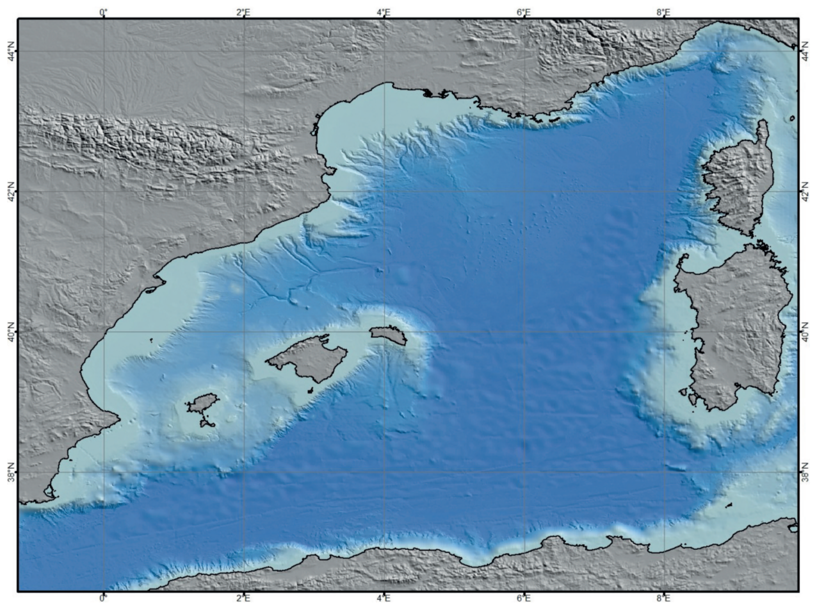


Figure 2. The highest density of Mediterranean submarine canyons is found in the northwestern Mediterranean depicted here. Composite image based on data sets from the MediMap Group (2005) and GEBCO Digital Atlas (IOC, IHO and BODC 2003).

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.

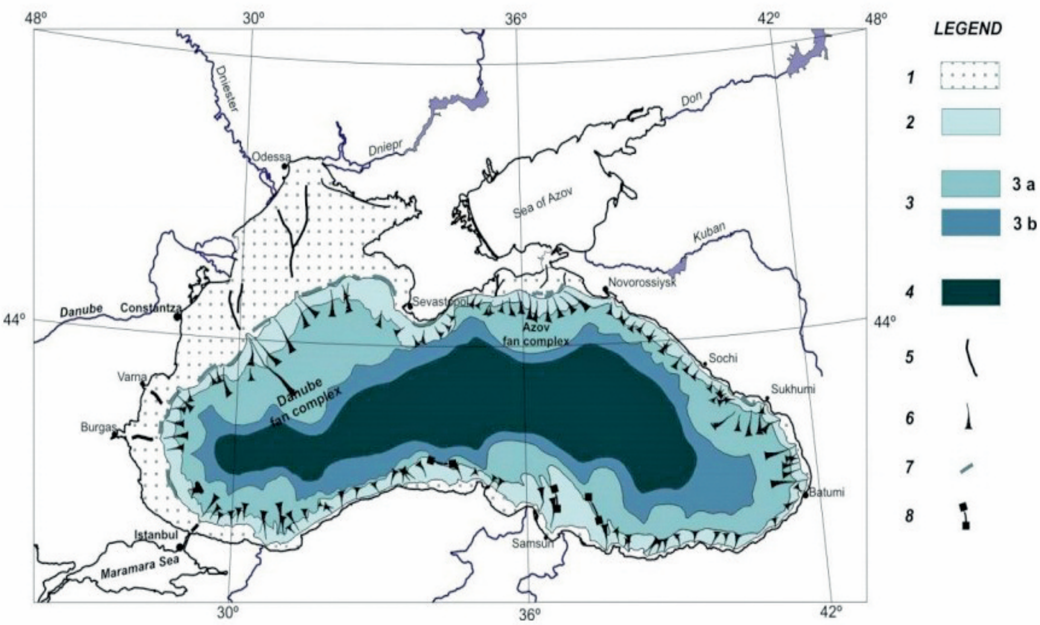


Figure 3. Geomorphologic zoning of Black Sea (from Popescu *et al.* this volume). Color coding and symbols: 1. continental shelf; 2. continental slope; 3. basin apron; 3 a. deep sea fan complexes; 3 b. lower apron; 4. deep sea (abyssal) plain; 5. paleo-channels on the continental shelf filled up with 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.

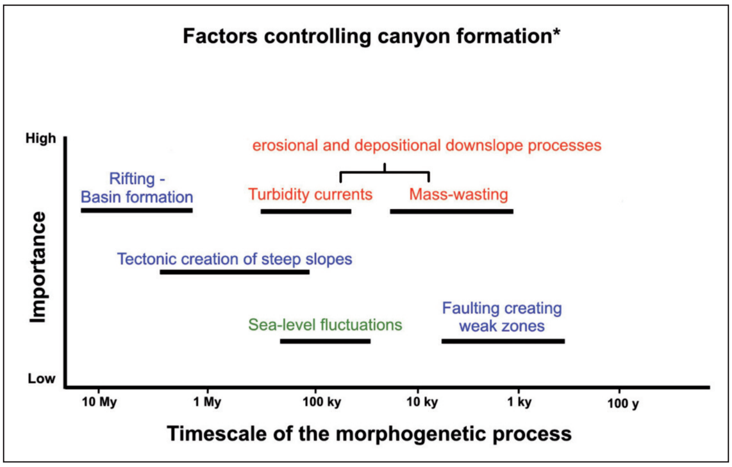


Figure 4. Factors controlling canyon formation over geological time.

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.

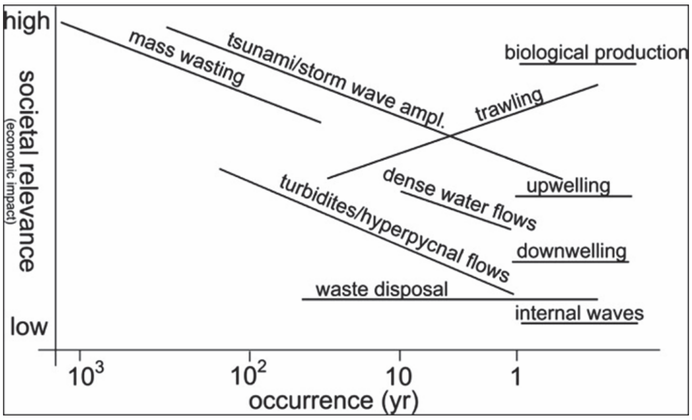


Figure 5. Factors affecting canyon dynamics over the short term.

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^o 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.

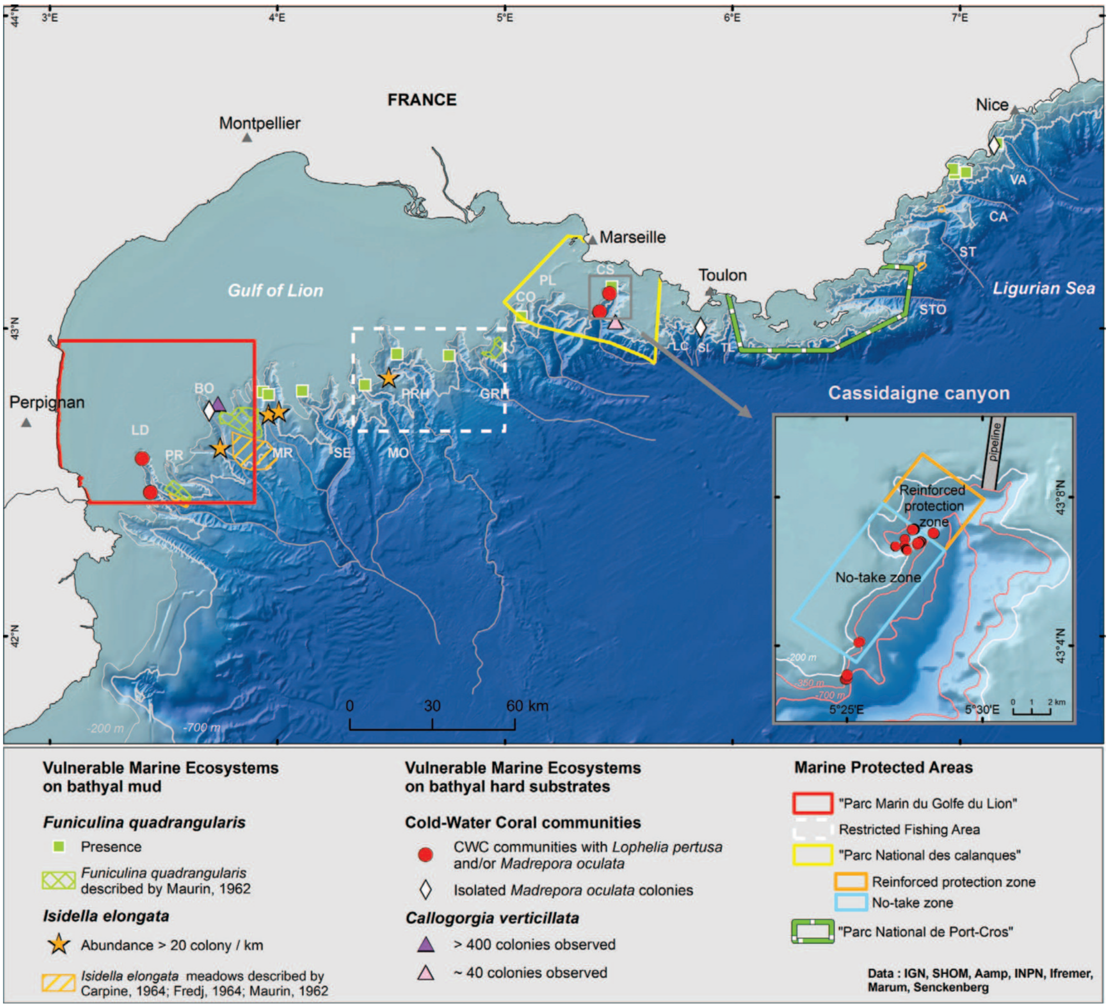


Figure 6. Geographical localisation of the submarine canyons that benefit or not of some protection in the French coastal waters of the Mediterranean Sea. Submarine canyons from West to East: LD: Lacaze-Duthiers, PR: Pruvost, BO: Bourcart (Aude), MR: Marti (Hérault), SE: Sète, MO: Montpellier, PRH: Petit 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.).

<u>Among the top priorities identified by our group:</u>

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.

Geomorphology of Mediterranean submarine canyons in a global context – Results from a multivariate analysis of canyon geomorphic statistics

Peter T. Harris and Miles Macmillan-Lawler

GRID-Arendal, Norway

Abstract

Submarine canyons in the Mediterranean and Black Seas stand out as globally different based on studies of global canyon geomorphology; they are more closely spaced, more dendritic (more limbs per unit area), shorter, have the smallest mean area, are among the most steep and have a smaller depth range than canyons that occur in other regions of the world. Here we present the results of a multivariate analysis of submarine canyon geomorphology to explore in more detail the apparently unique attributes of Mediterranean canyons. We find that Mediterranean canyons can be divided into six Classes, dominated by "Class 4" that is characterized by small area, close canyon spacing and a relatively high percentage of shelf incising canyons. On a global basis, Class 4 canyons are found to occur mainly (68%) on active continental margins. Examples of other regions in the world containing large numbers of Class 4 canyons are described.

1. Introduction

Submarine canyons in the Mediterranean and Black Seas stand out as globally different based on studies of global canyon geomorphology (Harris and Whiteway, 2011; Harris *et al.*, 2014a). Mediterranean canyons are more closely spaced, more dendritic (more limbs per unit area), shorter, have the smallest mean area, are among the most steep and have a smaller depth range than canyons that occur in other regions of the world. The question arises: "What physical processes explain these observed geomorphic attributes that are unique to Mediterranean canyons?"

The explanation for these differences is not simply due to a difference in data quality for the Mediterranean compared with other areas. The bathymetric models used by Harris and Whiteway (2009) and by Harris *et al.* (2014a) used versions of the Smith and Sandwell (1997) satellite altimetry dataset. The SRTM PLUS 30 v7 arc second model (Becker *et al.*, 2009) incorporated data from the Mediterranean margin of the highest quality (based on multibeam sonar data; Amante and Eakins, 2009; Becker *et al.*, 2009). But this factor does not explain the differences in observed geomorphology. Take canyon spacing, for example; some locations exhibiting close canyon spacing, such as the South Pacific, are not based on exceptionally high-quality data (Harris and Whiteway, 2011). Furthermore, locations having excellent data quality do not necessarily exhibit closely-spaced canyons, such as the margins of Japan and of the United States. Inspection of the global database for canyon length, slope, area and depth range confirms the view that the observed differences cannot be explained by data quality alone.

Other factors that might explain the geomorphic attributes unique to Mediterranean canyons include global sea level changes and density currents (Harris and Whiteway, 2011; Harris *et al.*, 2014a). Sea level lowering and desiccation of the Mediterranean basin that occurred during the late Miocene "Messinian Salinity Crisis" (e.g. Lofi *et al.*, 2005; CIESM, 2007) may have played a role in regional canyon development. The subaerial exposure and erosion of the continental margins bordering the Mediterranean are well documented in the literature (Hsü *et al.*, 1978; Druckman *et al.*, 1995; Rouchy and Caruso, 2006) and this phase of subaerial erosion is a unique feature of that region's geological history. The incision of the margin by rivers during this period would have created incipient canyons that were further developed by submarine processes following re-filling of the Mediterranean basin. However, tectonic uplift and margin progradation will have significantly modified or masked many canyons formed during the late Miocene, particularly along the northern active margin of the Mediterranean (e.g. Bertoni and Cartwright, 2005; Ridente *et al.*, 2007). A large percentage of shelf-incising canyons might be expected if subaerial erosion had played a major role in canyon development, and yet the Mediterranean does not in fact have a large percentage of shelf-incising canyons compared with other regions of the world (Harris and Whiteway, 2009).

Another possibility is the role played by erosive density currents formed in winter by cooling of shelf water masses, which cascade down submarine canyons. In the Gulf of Lion, down-canyon current speeds of up to 85 cm s^{-1} have been measured at 5m above bottom in 750 m water depth associated with winter cooling events (Canals *et al.*, 2006). Similar oceanographic processes have been invoked by Mitchell *et al.* (2007) to explain the headward erosion of Bass Canyon located in southeastern Australia during the Pleistocene. But it is not clear how this process alone could explain the geomorphic differences observed.

In order to explore possible reasons behind the geomorphic differences between the Mediterranean and other canyons in the world ocean, a new global database of submarine canyons (Harris *et al.*, 2014a) is here analysed using multivariate statistical methods. The new geomorphic data are based on interpretation of the Shuttle Radar Topography Mapping (SRTM30_PLUS) 30-arc second database (Becker *et al.*, 2009) as modified by Harris *et al.* (2014a) to include better quality data in the region around Australia. "Large" canyons were mapped in this study based on the definition of Harris and Whiteway (2011), which requires canyons to extend over a depth range of at least 1,000 m and to be incised at least 100 m into the slope at some point along their thalweg. Differences in canyon morphology highlighted by the results of multivariate analysis will be presented and discussed with the aim of seeking further possible explanations for the unique geomorphic attributes exhibited by Mediterranean canyons.

2. Methods - Multivariate analysis of canyons

A total of 9,477 submarine canyons are included in the global database compiled by Harris *et al.* (2014a) which also provides the compiled geomorphic attributes for each canyon, used here as input variables for a multivariate analysis. The input variables used are length, width, mean canyon depth, canyon depth range (delta depth), canyon spacing and the frequency of occurrence of shelf-incising canyons. Detailed descriptions of these variables are as follows:

Length: the maximum length of the canyon as calculated using a bounding box.

Width: the maximum width of the canyon as calculated using a bounding box.

Mean depth: the mean depth of the canyon polygon.

Delta Depth: the difference between the minimum depth and maximum depth within the canyon.

Spacing: the distance between adjacent canyons measured as the distance to the nearest canyon.

Frequency of occurrence of shelf-incising canyons: this is a measure of the area of shelf incising canyons divided by the total area of canyons that occurs within a given area, expressed as a percentage. The number was calculated as the percent of area of shelf incising canyon polygons occurring within a search radius of 500 cells.

The variables for each canyon were calculated in ArcGIS based on the geometry of the canyons and analysis of the modified SRTM30_PLUS bathymetric model. Each of the six variables was rasterised to a standard 0.5 minute grid (consistent with the modified SRTM30_PLUS bathymetric model). Each variable was scaled so that its range was between 0 and 100 to ensure equal weighting in the classification process using a linear transformation. The classification used the Iso cluster unsupervised classification algorithm in ArcGIS, run for between 3 and 20 classes.

3. Results

There are 817 canyons in the Mediterranean and Black Seas (refereed to here as simply the Mediterranean), which is the focus of the analysis presented here. The first step in our analysis was to calculate the discrete clusters for different canyon classes calculated for the global database of 9,477 canyons and then examine the numbers of canyons in each cluster occurring in the Mediterranean. The number of canyons from 3 to 20 clusters that occur in the Mediterranean (shown in Table 1) illustrates that with 6 clusters there are 4 significantly large populations in the Mediterranean (i.e. having more than 20 members; Classes 1, 3, 4 and 5). Adding additional clusters does not result in the creation of a greater number of significantly large clusters. Hence, six clusters was the number used in the present study to assess canyon populations.

Table 1. Number of canyons from the Mediterranean according to Class for differing numbers of clusters calculated for the global canyon database. With six clusters there are four significantly large populations in the Mediterranean (i.e. having more than 20 members; Classes 1, 3, 4 and 5). Adding additional clusters does not result in the creation of a greater number of significantly large clusters. Hence, six clusters was the number used in the present study to assess canyon populations.

Canyon Classes	3 Cluster	4 Cluster	5 Cluster	6 Cluster	7 Cluster	8 Cluster	9 Cluster	10 Cluster	11 Cluster	12 Cluster	13 Cluster	14 Cluster	15 Cluster	16 Cluster	17 Cluster	18 Cluster	19 Cluster
1	78	113	47	37	41	18	22	41	22	32	17	18	17	16	11	14	14
2	736	1	1	1	3	3	5	13	13	11	12	11	18	10	12	10	11
3	3	700	507	143	0	0	0	1	2	0	1	3	8	10	7	8	3
4		3	260	614	367	118	177	0	114	34	11	0	1	3	4	3	3
5			2	22	395	551	4	69	0	490	0	8	5	0	1	4	1
6				0	11	8	461	455	0	238	151	0	0	1	101	0	13
7					0	103	9	225	495	1	0	188	152	158	2	0	0
8						1	139	5	157	5	323	15	3	16	55	105	126
9							0	8	7	6	274	443	310	0	0	17	28
10								0	7	0	6	9	284	358	285	0	1
11									0	0	18	0	5	227	290	318	11
12										0	4	118	0	3	6	255	371
13											0	4	19	0	0	73	205
14												0	4	12	19	0	5
15													0	3	21	3	0
16														0	3	4	3
17															0	3	11
18																0	2
19																	0

3.1 Principle Component Analysis

Geomorphic attributes of six canyon classes for the global ocean and for the Mediterranean (Tables 2 and 3, respectively) provide the basis for the assessment of the geomorphic attributes that characterize each type. A principle component analysis (PCA) was conducted on the global dataset

(Appendix A) to highlight the most important characteristics defining each canyon type (i.e. the longest and most coherent eigenvectors).

Table 2. Global canyon geomorphic statistics with standard deviations (SD). See text for description of variables.

Class	Number	Average area (km2) ± SD	Average delta depth (m) ± SD	Average mean depth (m) ± SD	Average length (km) ± SD	Average width (km) ± SD	Spacing (km) ± SD	Incisedness (%)
1	2968	325 ± 429	1,634 ± 683	2,648 ± 950	36 ± 26	13 ± 10	15.0 ± 55.0	5%
2	159	3,636 ± 2,704	2,851 ± 985	2,739 ± 642	163 ± 50	58 ± 30	13.7 ± 25.8	6%
3	2783	391 ± 558	2,026 ± 976	2,464 ± 1,071	41 ± 32	14 ± 12	8.25 ± 8.77	31%
4	3154	237 ± 309	1,578 ± 594	1,856 ± 968	30 ± 21	11 ± 9	9.64 ± 14.6	61%
5	378	1,754 ± 1,445	3,514 ± 1,124	2,056 ± 699	102 ± 49	40 ± 24	15.8 ± 35.3	72%
6	35	9,944 ± 5,417	3,669 ± 1,159	2,468 ± 627	286 ± 62	116 ± 43	11.4 ± 21.7	73%
Total	**9477**	**463 ± 1,041**	**1,833 ± 895**	**2,308 ± 1,037**	**41 ± 38**	**15 ± 16**	11.2 ± 33.3	**34%**

Table 3. Mediterranean canyon geomorphic statistics with standard deviations (SD). See text for description of variables.

Class	Number	Average area (km2) ± SD	Average delta depth (m)	Average mean depth (m) ± SD	Average length (km) ± SD	Average width (km) ± SD	Spacing (km) ± SD	Incisedness (%)
1	37	395 ± 436	1,565 ± 686	2,135 ± 820	44 ± 32	14 ± 9	16.0 ± 23.0	10%
2	1	3,510	3,107	1,646	159	47	9.51	8%
3	143	146 ± 187	1,679 ± 775	1,926 ± 717	26 ± 20	9 ± 7	4.86 ± 5.59	33%
4	614	135 ± 199	1,465 ± 518	1,497 ± 658	23 ± 17	8 ± 7	5.77 ± 9.62	63%
5	22	1,849 ± 1,326	2,482 ± 728	1,500 ± 397	100 ± 53	59 ± 24	11.1 ± 39.7	74%
6	0	-	-	-	-	-	-	-
Total	**817**	**199 ± 426**	**1,536 ± 612**	**1,601 ± 698**	**27 ± 25**	**10 ± 11**	6.22 ± 12.0	**55%**

The PCA for Class 1 canyons shows that they are characterized by length and width (and hence area; component 1; canyon length, width and depth are highly correlated) and by mean depth (Component 2). Class 1 canyons are globally the second most common type (n = 2,968), but in the Mediterranean Class 1 canyons constitute only a small population (n = 37). In the Mediterranean Class 1 canyons are located almost exclusively in the Ionian Sea, Gulf of Sidra region (Fig. 1); there are also two occurrences in the Tyrrhenian Sea and two in the eastern Mediterranean. Class 1 canyons exhibit a large spacing both globally and in the Mediterranean (Tables 2 and 3). Because of their small number, Class 1 canyons are not expected to significantly influence the average geomorphic character of Mediterranean canyons as a whole (Tables 2 and 3).

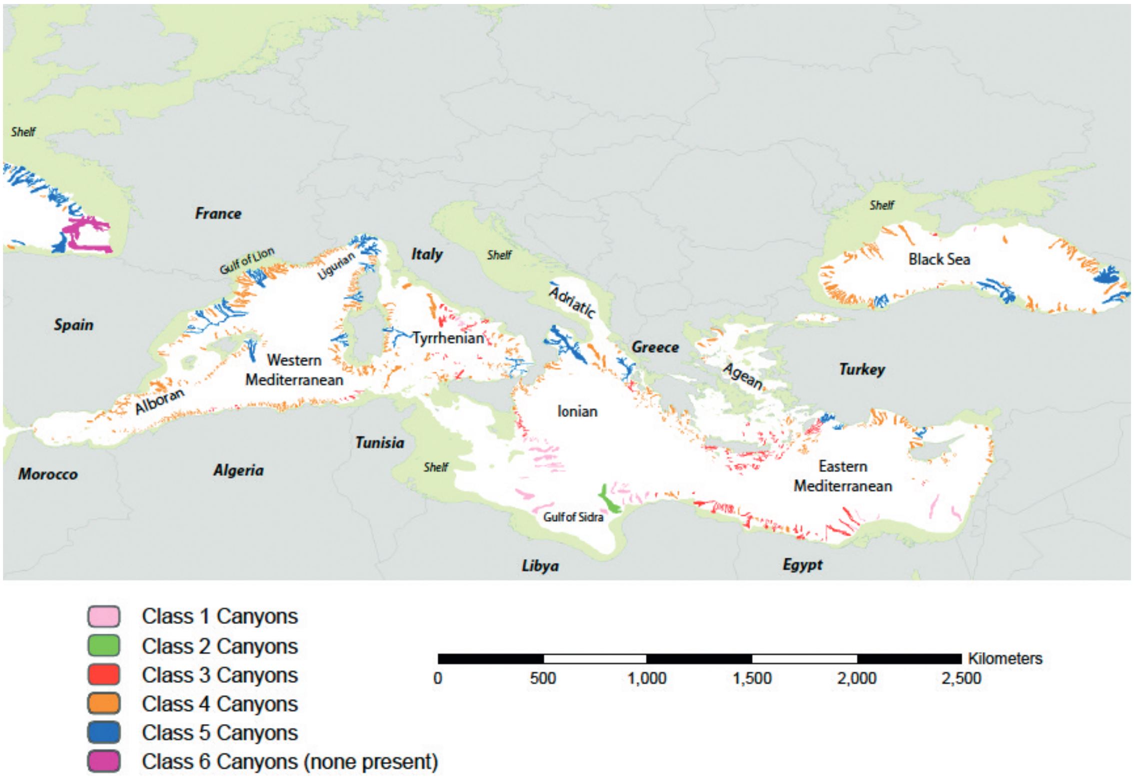


Figure 1. Distribution of canyon classes in the Mediterranean determined by multivariate statistical analysis of the global canyon data set as described in the text. Place names refer to discussion in the text. There are no Class 6 canyons in the Mediterranean Sea. The continental shelf area (after Harris *et al.*, 2014a) is shaded light green.

The PCA for Class 2 canyons shows that they are characterized by area, length and width (Component 1) and by depth range (delta depth, Component 2). Class 2 canyons are not a globally significant category (n = 159) and there is only one occurrence of Class 2 in the Mediterranean in the Gulf of Sidra (Fig. 1).

The PCA for Class 3 canyons shows that they are characterized by area, length and width (Component 1) and by the percentage of shelf incising canyons (incisedness) and canyon spacing (Component 2). Class 3 canyons are globally the third most common type (n = 2,968), and in the Mediterranean Class 3 canyons are the second most common type (n = 143; Tables 2 and 3). In the Mediterranean Class 3 canyons are located in the eastern Mediterranean off the coast of Egypt and south of Crete (Fig. 1). Class 3 canyons in the Mediterranean are significantly smaller in area than their global counterparts (146 ± 187 versus 391 ± 558 km^2, respectively) and also more closely spaced (4.86 ± 5.59 versus 8.25 ± 8.77 km^2, respectively) although their degree of incisedness in the Mediterranean (33%) is comparable to the global average (31%; Tables 2 and 3).

The PCA for Class 4 canyons shows that they are characterized by area, length and width (Component 1) and canyon spacing (Component 2); the percentage of shelf incising canyons (incisedness) is also important (Component 2). Class 4 canyons are globally the most common type (n = 3,154), and in the Mediterranean Class 4 canyons are also the most common type (n = 614; Tables 2 and 3). Class 4 canyons are widely distributed throughout the Mediterranean but are most common in the western Mediterranean and in the Black Sea (Fig.1). High concentrations occur in the Alboran Sea off the coast of Algeria, in the Gulf of Lion, the Ligurian Sea and in the western Black Sea. Class 4 canyons in the Mediterranean are significantly smaller in area than their global counterparts (135 ± 199 versus 237 ± 309 km^2, respectively) and they are also more closely spaced (5.77 ± 9.62 versus 9.64 ± 14.6 km^2, respectively). As in the case of

Class 3 canyons, the degree of incisedness of Class 4 canyons in the Mediterranean (63%) is comparable to the global average for that Class (61%; Tables 2 and 3).

The PCA for Class 5 canyons shows that they are characterized by length, width and area (Component 1) and by delta depth and mean depth (Component 2). Class 5 canyons are not common globally (n = 378), and there are only a small number of them in the Mediterranean (n = 22). Class 5 canyons exhibit a large spacing both globally and in the Mediterranean (Tables 2 and 3). Because of their small number, Class 5 canyons are not expected to significantly influence the geomorphic character of Mediterranean canyons as a whole (Tables 2 and 3).

Class 6 canyons are globally rare (n = 35) and there is no occurrence of a Class 6 canyon in the Mediterranean. Class 6 canyons are the world's largest, having the greatest mean area, length, width, mean depth, delta depth and percentage of incisedness. As noted by Harris *et al.* (2014a), the world's largest canyons tend to occur in the polar regions of the oceans.

3.2 Assessment of Class 4 canyons outside of the Mediterranean

From the above it can be seen that Class 4 canyons are numerically dominant and therefore exert a dominant influence on canyon geomorphic attributes that characterise the Mediterranean canyons. Therefore an assessment of the occurrence of Class 4 canyons beyond the Mediterranean is warranted. An assessment of locations around the world where large numbers of Class 4 canyons occur outside of the Mediterranean has been carried out using the focal variety tool in ArcGIS (Fig. 2) and the results are described here.

In the Celebes Sea – Timor Sea region (Fig. 2A) concentrations of Class 4 canyons occur around the island of Sulawesi in the Flores Sea and along the southern margin of the island of Java. Several Class 4 canyons feed into Bone Gulf in southern Sulawesi and are visible in multibeam imagery presented by Camplin and Hall (2014) who describe a regional Pliocene tectonic event that caused a "major influx of clastic sediments from the north and the development of a southward-flowing canyon system". Class 3 canyons dominate in this region overall (Class 4 canyons are regionally subordinate to Class 3) and Class 5 canyons also occur in significant numbers.

Concentrations of Class 4 canyons occur off the east coast of Taiwan extending northwards into the East China Sea and around the Okinawa Trough (Japan; see Oiwane *et al.*, 2011); another group occurs on both the east and west coasts of the island of Kalusunan in the Philippines (Fig. 2B). These groups of Class 4 canyons are separated by a cluster of Class 3 canyons, located between Taiwan and Kalusunan.

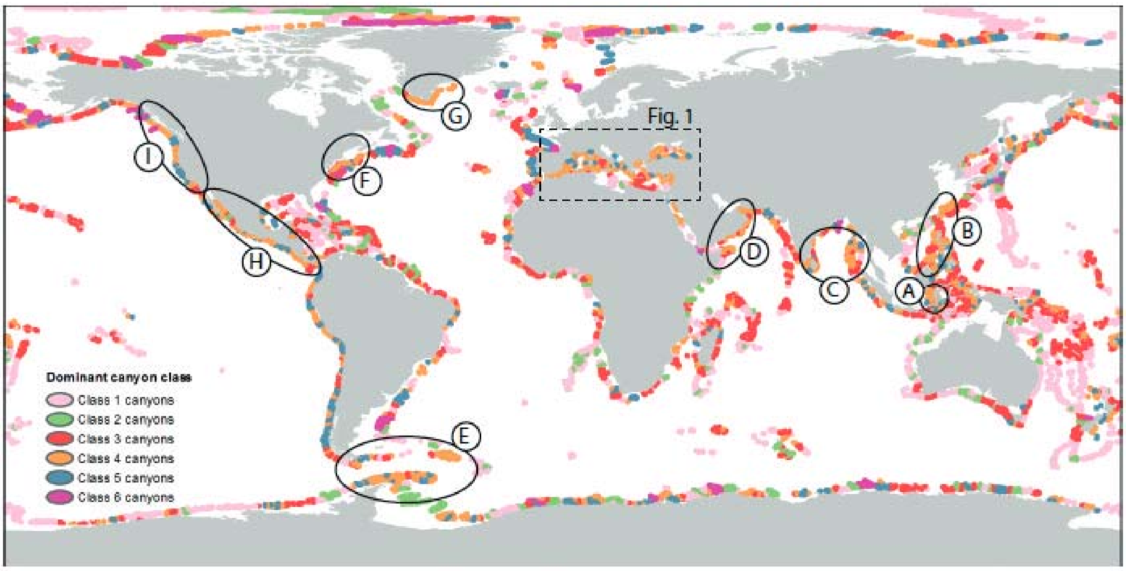


Figure 2. Map showing the global distribution of canyon classes produced using focal statistics. The majority canyon type over a 100 km moving window was calculated in ArcGIS. The map illustrates different regions containing local concentrations of Class 4 canyons (see text for details).

In the Bay of Bengal, Class 4 canyons outnumber all other classes and dominate the region (Fig. 2C). They are most common around the Andaman Islands and Sri Lanka. Other canyon classes are much less common and there are only a few groups of Class 3 and isolated occurrences of Class 5 canyons. The tectonic setting of this region is complex (Curray, 2014) since the Andaman Islands side of the Bay of Bengal is considered an active plate margin whereas Sri Lanka is considered to be a passive margin (Fig 3).

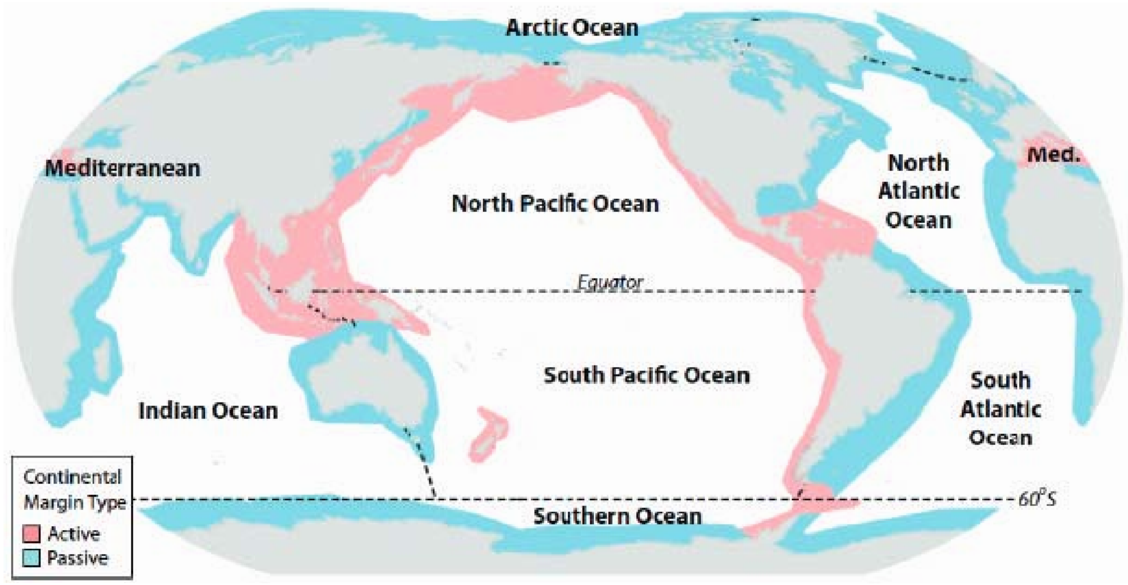


Figure 3. Map showing the global distribution of active and passive plate margins.

Further east adjacent to the Arabian Peninsula and Gulf of Aden, Class 4 canyons dominate the continental margin, with groups of Class 4 canyons interspersed with one or two Class 3 canyons (Fig. 2D). Here again the tectonic setting is complex with active seafloor rifting in the Gulf of Aden and plate collision between India and the Arabian Plate (Fournier *et al.*, 2010).

Drake Passage contains concentrations of Class 4 canyons (Fig. 2E), especially off the southern coast of Tierra del Fuego, adjacent to the Antarctic Peninsula and around the island of South Georgia. In this region Class 4 canyons outnumber all other Classes. They are interspersed with some Class 5 canyons and with lesser numbers of Class 3 canyons.

Several large groups of Class 4 canyons are located off the coast of the eastern United States (Fig. 2F) and southern Greenland (Fig. 2G), providing examples of their occurrence along a passive continental margin. One continuous group of around thirty Class 4 canyons is located offshore of Chesapeake Bay and another large group is located east of Cape Cod (Shepard, 1981; Mitchell, 2008). These groups are interspersed with isolated Class 5 and 6 canyons and small groups of Class 3. A group of about 18 Class 4 canyons extend without interruption along the southern and southeastern margins of Greenland.

Concentrations of Class 4 canyons occur in the Gulf of California, around the southern tip of the Baja California Peninsula and as an extensive semi-continuous group, interspersed with individual, isolated Class 5 canyons, extending along the western coast of Mexico (Reimnitz and Gutiérrez-Estrada, 1970) from Puerto Vallarta southwards to Guatemala, El Salvador and Nicaragua (Fig. 2H). Class 4 canyons also dominate along large sections of the eastern margin of South America (Fig. 2).

In the northeast Pacific, along the western coasts of British Columbia (Canada) and the United States, Class 4 canyons dominate over large areas (Fig. 2I). One continuous group extends along the entire coast of British Columbia (apart from one large Class 6 canyon) and a semi-continuous group extends northwards from San Francisco to the Columbia River mouth, interspersed with a few Class 5 canyons (Shepard, 1981). Tectonic processes are thought to have exerted control on the geomorphology of some British Columbia canyons (Harris *et al.*, 2014b) and on some California canyons (Le Dantec *et al.*, 2010) but not on others (Gardner *et al.*, 2003).

4. Discussion

4.1 Significance of Mediterranean canyon statistics

Out of 817 canyons in the Mediterranean, 614 (over 75%) are classified here as Class 4, much more than the global average of Class 4 comprising 33% of all canyons. Therefore, canyon geomorphologic statistics in the Mediterranean are strongly governed by this Class and the overall attributes of small area, short length, narrow width and close canyon spacing are attributable to the dominance of Class 4 canyons in the Mediterranean region.

An assessment of other locations around the world where large numbers of Class 4 canyons occur (Fig. 2) suggests a pattern of occurrence: Class 4 canyons appear to occur more commonly along active plate margins compared with passive margins (Fig. 3). In fact the number of Class 4 canyons occurring along active margins (n = 1,970) is much greater than the number found along passive margins (n = 908); i.e. 68% of Class 4 canyons occur on active margins. But there is considerable variation regionally as described above.

Some other clear associations are that Classes 3, 4 and 5 canyons are often found together in the examples studied (Fig. 2). However, whereas Class 3 and 4 canyons tend occur as discrete clusters of five or more, Class 5 canyons are often solitary and occur interspersed with Class 4 canyons. Controls of tectonism and sediment input exhibit broad variations and there is no single process that appears to dominate in the formation of Class 4 canyons.

4.2 Relevance of canyon geomorphology in canyon evolution

Shepard (1981) summarized the two main processes attributed to canyon formation: i) mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. These two processes (Fig. 4) are not mutually exclusive and are probably contemporaneous and spatially congruous on many slopes, but considering the two processes separately provides a framework to interpret the statistical data we now have available on canyon geomorphic attributes.

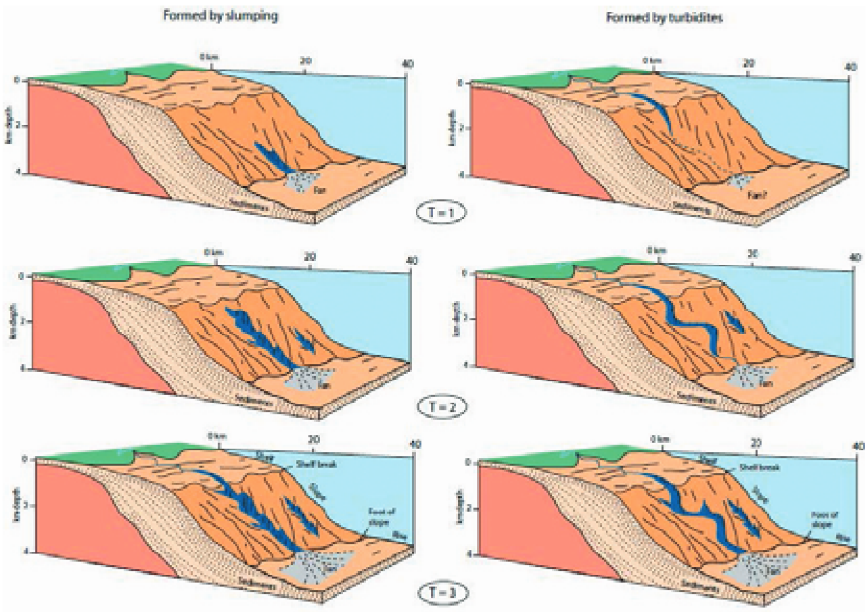


Figure 4. Schematic diagrams showing evolution of submarine canyons over three time slices (T1 to T3) by two processes: i) mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. The meandering course of deeply incised, mature canyon thalwegs formed by erosion by turbidites was suggested by Gee *et al.* (2007).

Modelling has revealed the importance of headward erosion driven by sediment flow downcutting, in which tributaries are the precursors of larger submarine canyon systems (Pratson and Coakley, 1996). Enlargement by slumping has been shown to explain the morphology of some canyon systems (Sultan *et al.*, 2007). Fluid escape along a section of continental slope prone to slump-failure may theoretically produce a self-organised canyon (Orange *et al.*, 1992).

The two processes (Fig. 4), taken as a model for canyon formation, make at least three predictions that can be tested:

1. The occurrence of shelf-incising canyons should correlate approximately with regionally averaged sediment discharge to the coast.
2. Shelf incising canyons are on average larger than blind canyons because they are only formed towards the end of the evolutionary cycle involving incipient blind canyons.
3. The number of blind canyons should exceed the number of shelf incising canyons because shelf incising canyons are only formed towards the end of the evolutionary cycle involving (often several) incipient blind canyons.

Prediction Number 1 was addressed by Harris and Whiteway (2011) who plotted modeled sediment discharge data (Ludwick and Probst, 1998) versus the percentage of shelf incising canyons for all non-polar margins on earth (Fig. 5). The resulting plot demonstrates that a strong relationship (r = 0.68) exists between these parameters, as the proposed model predicts.

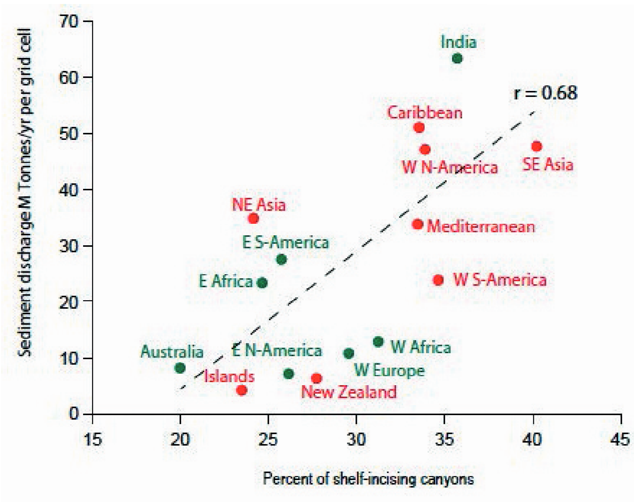


Figure 5. Plot of the fraction of canyons occurring in each geographic region (excluding the Arctic and Antarctic) that incise the continental shelf (modified from Harris and Whiteway, 2011) versus the rate of sediment discharge modelled by Ludwig and Probst (1998), measured in million tonnes per year per grid cell (2o Lat.itude by 2.5o Longitude). Sediment discharge values plotted here are estimated from Ludwig and Probst (1998; their figure 11) by taking the average value for modelled grid cells occurring within the specified geographic regions. The linear correlation coefficient r = 0.68 for the data shown. Active regions are shown in red and passive in green.

The second and third predictions can be tested based on statistical data (Table 4) published by Harris *et al.* (2014). The data show that the average size of shelf- incising canyons is more than twice that of blind canyons, as per prediction number 2. Furthermore, blind canyons outnumber shelf-incising canyons by a ratio of more than 3 to1 (see Table 4), which supports prediction number 3. What can also be seen is that the statistics are consistent across all ocean regions; the average size of shelf- incising canyons exceeds that of blind canyons, and blind canyons outnumber shelf-incising canyons in every ocean region. The Mediterranean is no exception to this globally consistent pattern (Table 4).

Table 4. Statistics on shelf incising and blind canyons (from Harris *et al.,* 2014). The data show that blind canyons outnumber shelf incising canyons by a ratio of more than 3 to1, whilst the average size of shelf incising canyons is more than twice that of blind canyons.

Ocean	All canyons No.	Self-incising No.	Blind canyon No.	Self-incising average size km^2	Blind canyon average size km^2
Arctic Ocean	404	75	329	2,160	600
Indian Ocean	1,590	295	1,295	754	415
Mediterranean Black Sea	817	307	510	307	134
North Atlantic	1,548	293	1,255	997	355
North Pacifie	2,085	489	1,596	751	281
South Atlantic	453	73	380	894	594
South Pacifie	2,009	368	1,641	584	292
Southern Ocean 5	71	176	395	1,104	949
All Oceans	9,477	2,076	7,401	777	375

Conclusions

The unique geomorphic attributes of Mediterranean canyons are due to the dominance of Class 4 canyons in that region. Apart from their occurrence on active margins, there is no other obvious common factor among the global occurrences of Class 4 canyons (Fig. 2) that has emerged from our assessment. The identification of other factors (apart from their occurrence on active margins) that may control the formation of Class 4 canyons awaits future research.

The model for canyon formation put forward by Shepard (1981) includes two basic processes: i) the mass wasting and retrograde slumping of the continental slope and ii) erosion by turbidity currents sourced from the continental shelf. This model provides the basis for making three predictions that have been tested using available data:

1. the occurrence of shelf-incising canyons correlates approximately with regionally averaged sediment discharge to the coast;

2. shelf incising canyons are on average larger than blind canyons; and

3. the number of blind canyons exceeds the number of shelf incising canyons.

The available data are consistent with these three predictions. Furthermore, the geomorphic data for the Mediterranean region shows that the average size of shelf- incising canyons exceeds that of blind canyons, and blind canyons outnumber shelf-incising canyons.

---

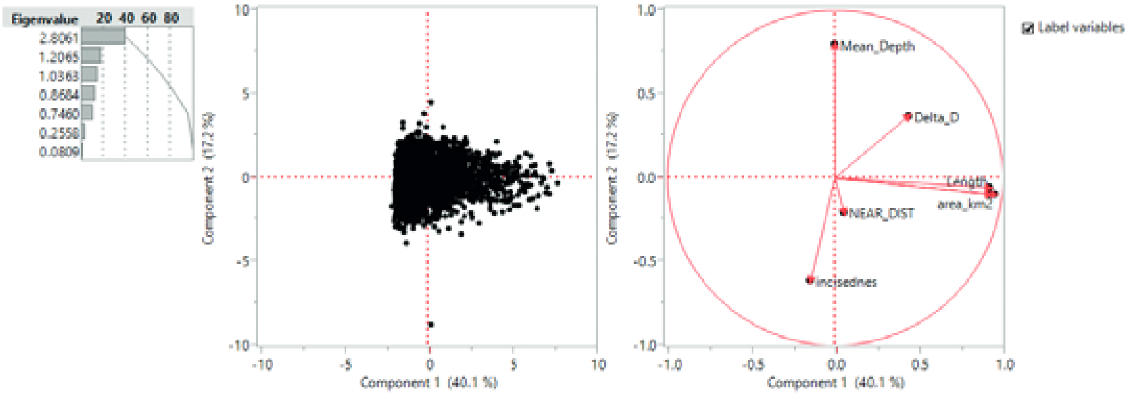
* this chapter is to be cited as:

Harris P.T., Macmillan-Lawler M. 2015. Geomorphology of Mediterranean submarine canyons in a global context – Results from a multivariate analysis of canyon geomorphic statistics. pp. 23 - 35 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.

Appendix A. Principal Component Analysis, six classes

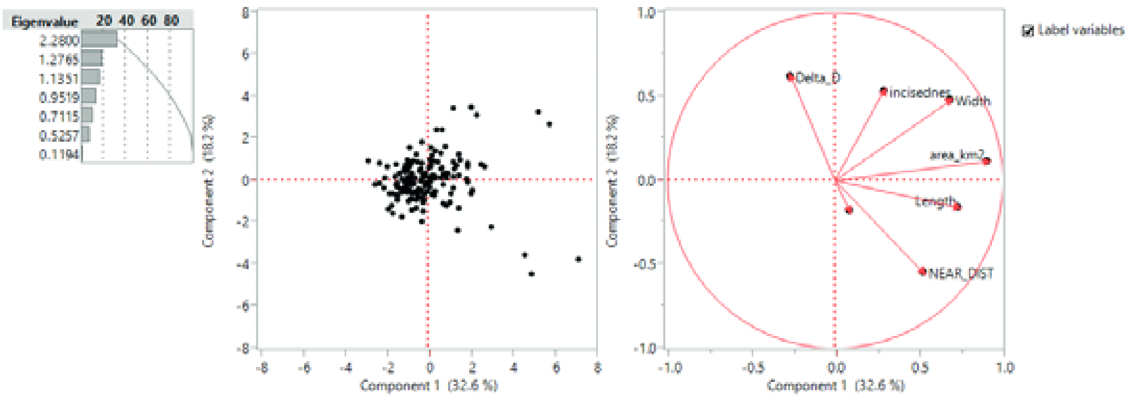
Class 1

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.951	-0.102	0.037	-0.084	0.162	-0.022	-0.224
Delta_D	0.440	0.370	-0.343	0.480	-0.567	-0.027	-0.022
Mean_Depth	-0.002	0.791	0.070	0.320	0.518	0.003	0.006
Length	0.917	-0.058	0.002	-0.029	0.053	0.375	0.107
Width	0.919	-0.098	0.010	-0.046	0.110	-0.337	0.136
Spacing	0.052	-0.204	0.863	0.442	-0.125	-0.002	-0.002
incisednes	-0.146	-0.616	-0.410	0.575	0.317	0.011	0.000



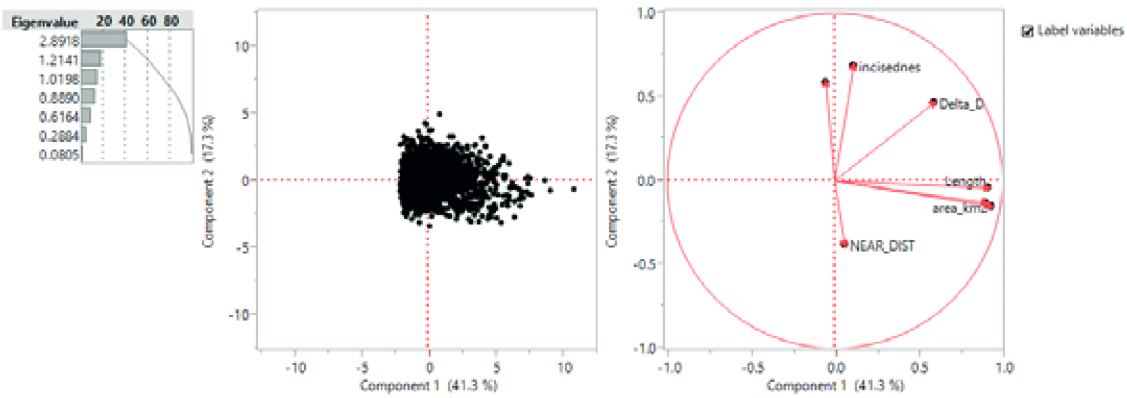
Class 2

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.909	0.113	0.156	-0.235	-0.037	-0.139	-0.247
Delta_D	-0.264	0.623	0.414	0.266	0.520	-0.175	-0.019
Mean_Depth	0.087	-0.181	0.783	0.443	-0.353	0.162	-0.004
Length	0.736	-0.161	-0.177	0.430	-0.026	-0.446	0.130
Width	0.689	0.477	0.235	-0.412	-0.043	0.182	0.196
Spacing	0.525	-0.550	0.020	0.122	0.546	0.330	0.008
incisednes	0.291	0.537	-0.490	0.511	-0.125	0.329	-0.053



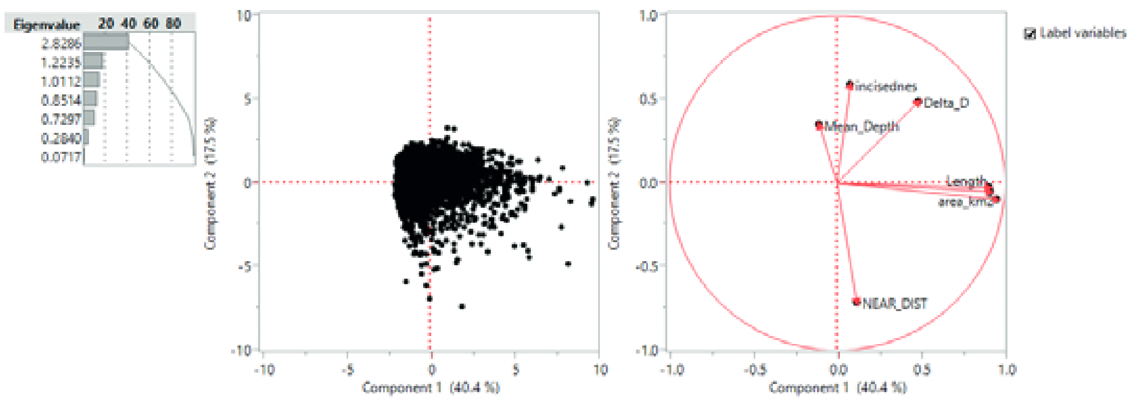
Class 3

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.936	-0.155	0.034	-0.053	-0.218	-0.011	-0.219
Delta_D	0.595	0.467	-0.120	-0.031	0.641	0.012	-0.035
Mean_Depth	-0.051	0.584	0.498	-0.617	-0.167	0.020	0.008
Length	0.911	-0.043	0.003	-0.033	-0.095	-0.376	0.129
Width	0.901	-0.133	-0.005	-0.027	-0.095	0.382	0.121
Spacing	0.059	-0.379	0.858	0.247	0.234	-0.009	0.000
incisednes	0.114	0.684	0.140	0.665	-0.239	0.018	0.000



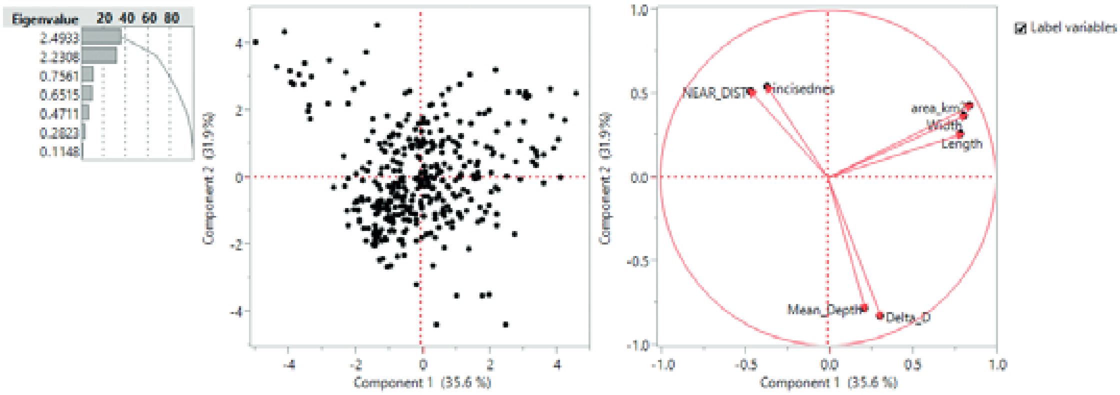
Class 4

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.950	-0.097	0.022	-0.011	-0.207	0.018	-0.210
Delta_D	0.487	0.488	0.136	-0.067	0.707	0.039	-0.024
Mean_Depth	-0.105	0.345	0.845	0.332	-0.214	0.009	0.004
Length	0.909	-0.027	0.034	0.004	-0.063	-0.396	0.103
Width	0.911	-0.051	0.004	-0.050	-0.152	0.353	0.129
Spacing	0.118	-0.715	0.068	0.611	0.310	0.024	0.001
incisednes	0.079	0.586	-0.522	0.600	-0.135	0.007	0.000



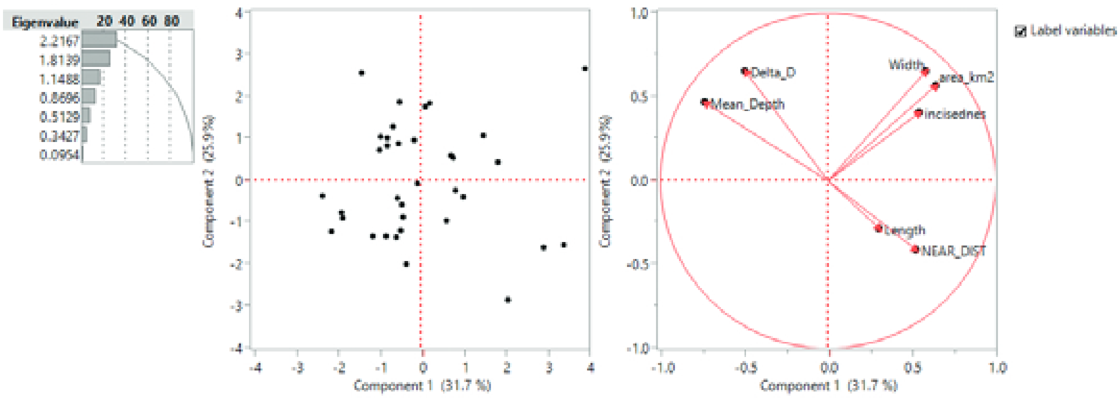
Class 5

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.850	0.425	0.065	0.133	0.092	0.012	-0.258
Delta_D	0.316	-0.827	0.070	0.160	0.190	0.386	0.019
Mean_Depth	0.223	-0.783	0.170	0.458	-0.064	-0.308	0.004
Length	0.791	0.258	-0.152	0.149	-0.489	0.111	0.109
Width	0.810	0.369	0.087	-0.050	0.389	-0.109	0.185
Spacing	-0.460	0.513	-0.417	0.566	0.166	0.056	0.025
incisednes	-0.359	0.537	0.717	0.231	-0.066	0.104	0.036



Class 6

	Prin1	Prin2	Prin3	Prin4	Prin5	Prin6	Prin7
area_km2	0.644	0.569	0.338	-0.249	0.120	0.201	-0.174
Delta_D	-0.494	0.653	0.055	0.322	0.377	-0.281	-0.050
Mean_Depth	-0.734	0.467	0.156	0.204	-0.047	0.411	0.082
Length	0.309	-0.286	0.876	0.101	0.160	-0.053	0.129
Width	0.585	0.654	-0.337	-0.251	0.119	-0.025	0.198
Spacing	0.530	-0.413	-0.349	0.502	0.361	0.210	-0.008
incisednes	0.548	0.408	0.064	0.581	-0.429	-0.086	-0.006



"Rocky" versus "Sedimentary" canyons around the Mediterranean and the Black Seas

Jean Mascle[1], Sébastien Migeon[2], Marianne Coste, Virginie Hassoun and Pierrick Rouillard

[1] *Observatoire Océanologique de Villefranche, Villefranche-sur-mer, France*
[2] *Geoazur, Sophia-Antipolis, France*

Introduction

Submarine canyons are commonly interpreted as erosive features and areas of bypassing for sediments, nutrients and organic matter (Normark and Carlson, 2003; Shepard, 1981;Twichell and Roberts, 1982). The largest canyons are classically 1000-1500 m deep, up to 20-50 km wide and several tens of kilometers long (Normark and Carlson, 2003; Harris and Macmillan-Lawler, this volume). Two main types of canyons are usually distinguished by geologists (Goff, 2001; Twichell and Roberts, 1982): ***(1)*** *immature canyons*. They consist of small and relatively straight features, often organized in clusters, and restricted to the continental slopes; submarine failure and mass wasting processes are the main mechanisms controlling their development, ***(2)*** *mature canyons*. These consist of rather wide submarine valleys deeply indenting the continental shelf and slope and fed by more or less continuous sediment supply delivered by river inputs and/or coastal currents.

For decades, almost since their discovery, the origin of canyons, particularly those of the Mediterranean Sea, has been a matter of strong scientific debate.

Canyon morphology is classically divided into four geomorphologic domains (Fig. 1): the head, the thalweg, the lateral walls and the distal reaches or mouth (Cronin *et al.*, 2005). ***(a)*** Most canyon heads are characterized by amphitheater-like features made of abundant small sedimentary scars due to repetitive small-scale mass-wasting processes (Green *et al.*, 2007). Heads are active areas in term of current activity and sediment transfer, which erode the upper slope ultimately up to the shelf break . ***(b)*** Canyon thalwegs can be either almost straight or quite sinuous depending of local slope angle variability, volume of sediment supplies and importance of tectonic controls (Laursen and Normark, 2002); canyon trends can effectively be largely controlled, and deflected, by fault scarps, active faulting (Çağatay *et al.*, this volume), margin tectonic uplifts (Ceramicola *et al.*, this volume). ***(c)*** Canyon walls may often be relatively steep (frequently up to 30-40°), sometimes nearly vertical; canyon lateral slopes may be affected by large sediment failures, erosional processes and dense flows. Depositional areas, expressed as terraces, confined levees and, sometimes, sedimentary ridges, can also develop in this setting (Babonneau *et al.*, 2004). ***(d)*** The transition between the distal domains of canyons and their depositional channels still remains difficult to image from subsurface geophysical data. These areas may be characterized by the development of thalweg channels when the canyons are progressively losing their topographic expression (Cronin *et al.*, 2005; see also Amblas *et al.*, this volume) and connect with more or less sinuous channel-levee systems such as in most major delta-related sedimentary cones (for example the Rhone or Nile cones).

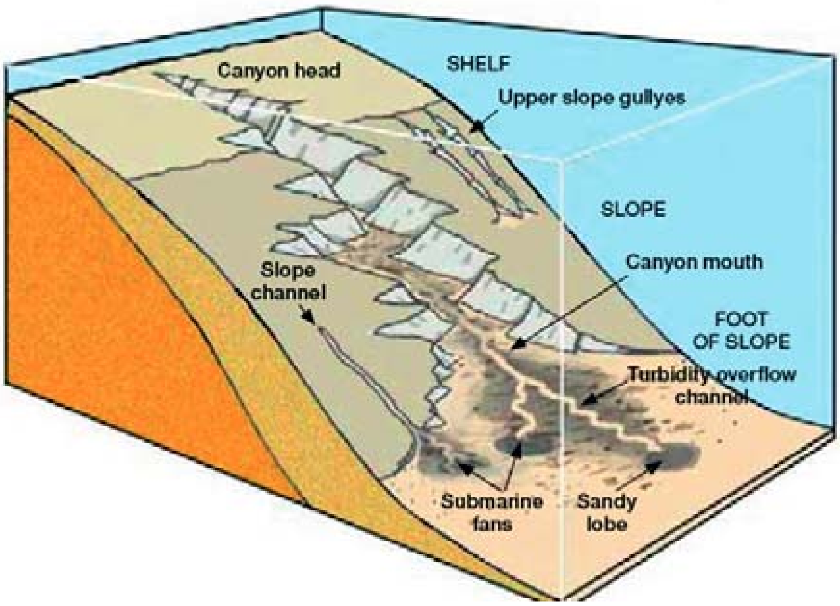


Figure 1. Schematic morphology of a submarine canyon (after Würtz, 2012).

In the Mediterranean Sea (Fig. 2) most major canyon systems appear superimposed on previous tectonic lineaments, such as fault systems issued from various rifting episodes (depending of the areas), from recent tectonic reactivation (Ceramicola *et al.*, this volume) and from active tectonics.

In the small Mediterranean basin canyon development may however rely on various processes, which can moreover be combined. Among them:

(a) aerial (or fluvial) erosion during low-stand sea levels, imaged as well by seismic data across continental shelves (Ebro, Nile; see Amblas *et al.*, this volume). In the western Mediterranean domain, such control may have been particularly intense during the Messinian event, when sea-level may have dropped up to 1.5 km;

(b) retrogressive erosion, triggered by repeated submarine landslides;

(c) frequent bypassing by debris flows, turbidity currents, hyperpycnal flows or up and down currents related to tides and even to internal waves.

Cascading currents, issued from processes of dense waters formation (see Puig *et al.*, this volume), have also been identified as one of the mechanisms generating seafloor erosion. Erosion leads itself to displacement of large volumes of sandy particles able to strongly impact thalweg morphologies (Gaudin *et al.*, 2006; Trincardi *et al.*, 2007).

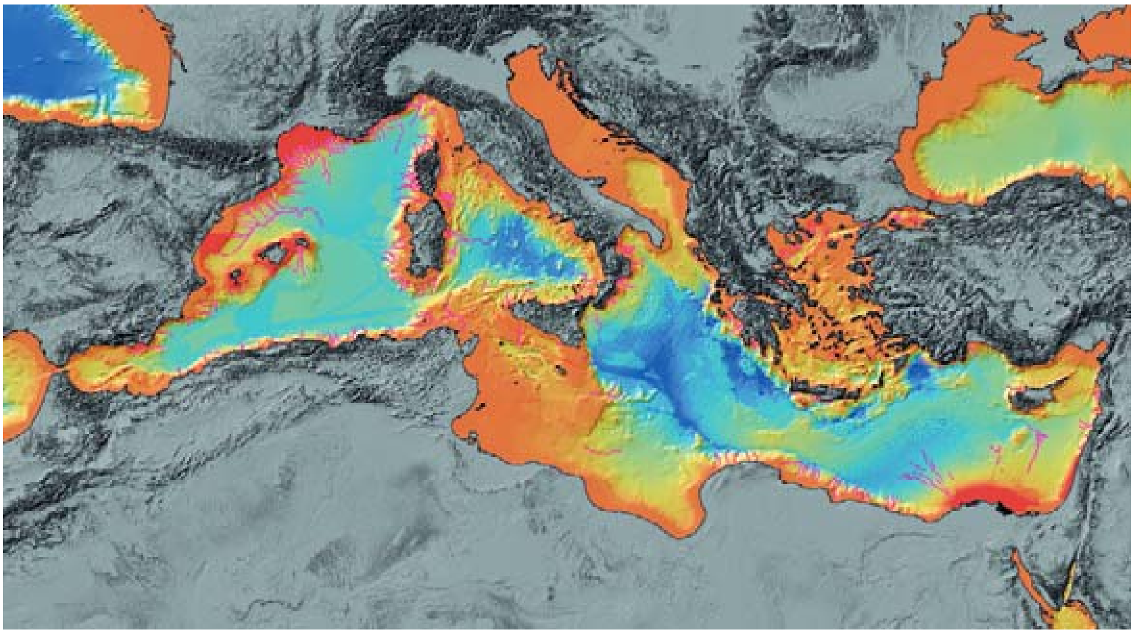


Figure 2. Morpho-bathymetry of the Mediterranean Sea showing the main canyon and channel systems around the basin; the northwestern Mediterranean margins appears by far to be the area where canyons are the most abundant. (after Migeon *et al.,* 2012).

We first present here a brief geological overview of submarine canyons around the Mediterranean Sea, based on recent detailed morpho-bathymetry maps of the Mediterranean Sea (see Fig. 2) and in part on a previous paper (Migeon *et al.*, 2012). We then discuss two case studies, which we consider to be representative of two *"end members"* of the large Mediterranean canyons families (see Harris and Macmillan-Lawler, this volume) at least from a geological point of view:

(1) "Rocky" canyons, which are indenting steep continental slopes, and along which hard rocks outcrops are often exposed; in their large majority these canyons are superimposed on lines of weakness due to past, recent or active tectonics; for a significant number of them they may also have been partly rejuvenated during a considerable sea-level drop which occurred few millions years ago during the Messinian event.

(2) "Sedimentary" canyons, that are partly fed and covered by recent soft sediments; these last features cut across wide and thickly sedimented continental shelves and slopes built in relation to submarine deltas expressed as large clastic cones; most of these sedimentary canyons lie at the mouth of major rivers such as the Ebro (Amblas *et al.*, this volume), the Danube (Popescu *et al.*, this volume) or, the Rhone and the Nile (this paper).

Among the "*rocky"* canyons we have selected the example of the *Riviera* and *Liguria* margins (Fig. 3). The same type of steep, and almost non-sedimented canyons, cut however across many other continental slope segments all around the Mediterranean Sea, including off Corsica, western Sardinia, Calabria, Algeria and along the southern Aegean domain.

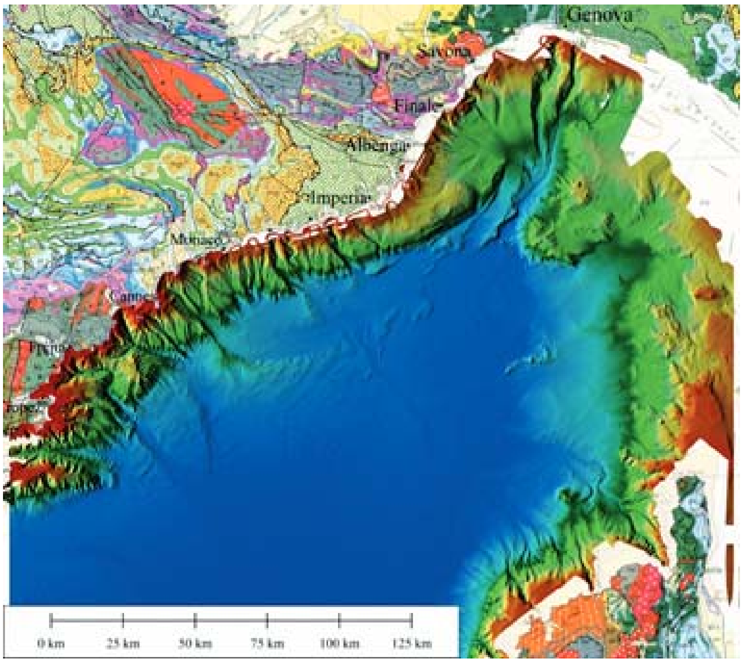


Figure 3. Main canyons of the Riviera/Liguria Margin from Nice to Genova and off northwestern Corsica (unpublished DTM at 25m based on swath bathymetry data; courtesy S. Migeon).

In the case of the western Mediterranean Sea we think that most of these features were first created when the continental slope was in its building, i.e. during the rifting and drifting episodes, approximately between 35 and 20 my ago, which led to the creation of this sub-basin. Today these canyons, whose upper domains have likely been rejuvenated as aerial valleys during the Messinian low stand, are directly crosscutting Paleozoic, Mesozoic and Alpines rocks.

As an example of the "*sedimentary*" canyons, we will focus here on the *Rosetta canyon,* which characterizes the Egyptian continental Margin and initiates just fifteen miles off Alexandria (Fig. 4). Today the *Rosetta* submarine canyon constitutes the unique marine exutory through which most of the sediment supplies transported by the Nile River are delivered and deposited on the Nile submarine cone and its northern bordering Herodotus abyssal plain (Rouillard, 2010; Migeon *et al.*, 2012).

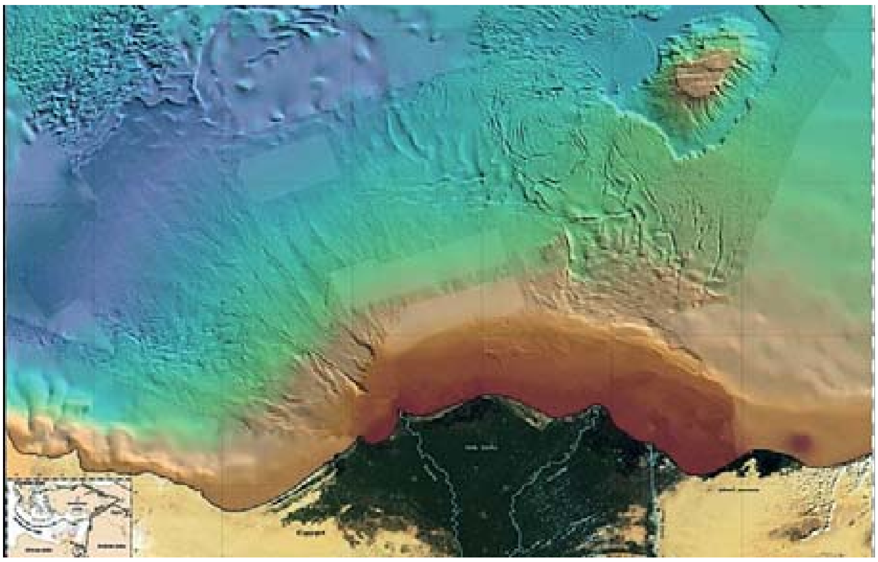


Figure 4. The Nile continental margin and the Rosetta canyon and channel/levees system (on the western border of the Nile margin) (after Sardou and Mascle, 2003).

A brief overview of the main Mediterranean Canyon systems

Recent detailed bathymetric syntheses of the Mediterranean basins (see Fig. 2) have made possible to highlight the strong contrasts not only between the western and eastern domains, but also between the various submarine canyon networks cutting across their respective continental margins.

- Western Mediterranean basin

Along the Western Mediterranean continental margins different areas, characterized by strongly contrasted canyon morphologies, can be distinguished (Fig. 5).

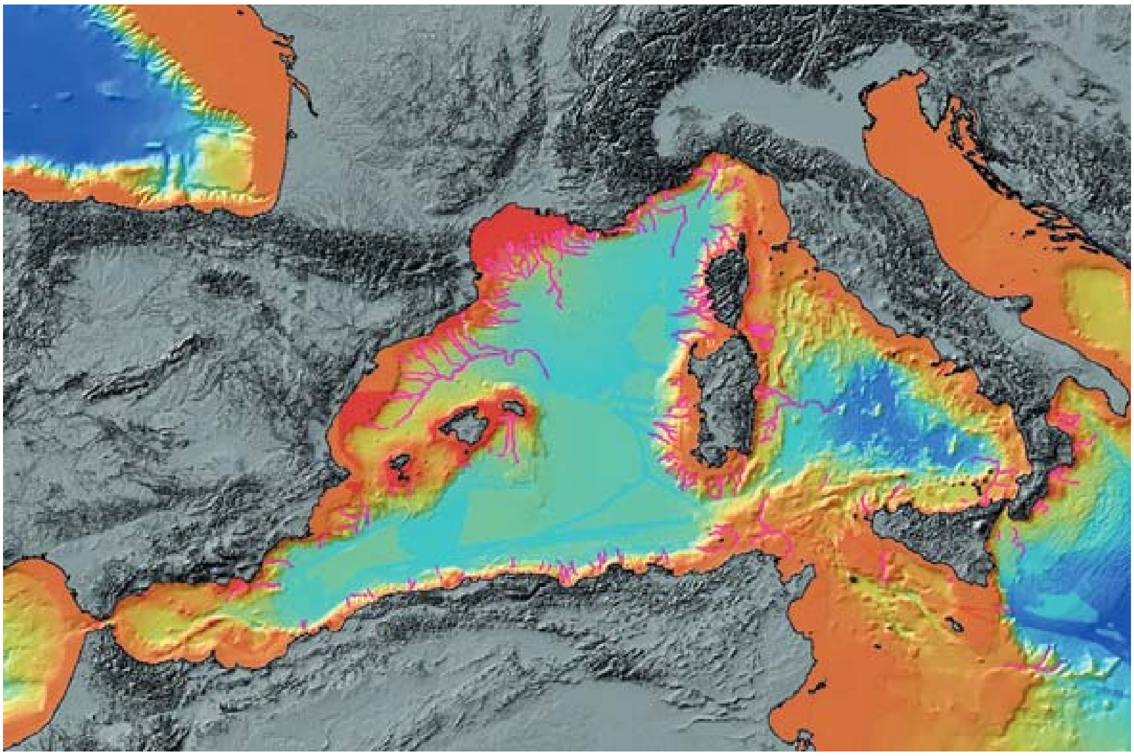


Figure 5. The main western Mediterranean Sea canyons systems (in purple) (after Migeon *et al.,* 2012).

While parts of these contrasts may relate to differences in resolution of available bathymetric data, Figure 5 clearly illustrates that the most important and widespread canyon system has developed along the Northwestern Mediterranean Sea continental slopes. There one may successively observe, from west to east, a network of canyons running across the Gulf of Valencia and Catalonia slopes, merging, at depth, into a long and meandering channel through which most of the Ebro sedimentary supplies are transported into the abyssal plain (see Amblas *et al.*, this volume). From the Pyrenean borders to the vicinity of Marseille, numerous canyons cut across the Gulf of Lion slope (Fig. 6).

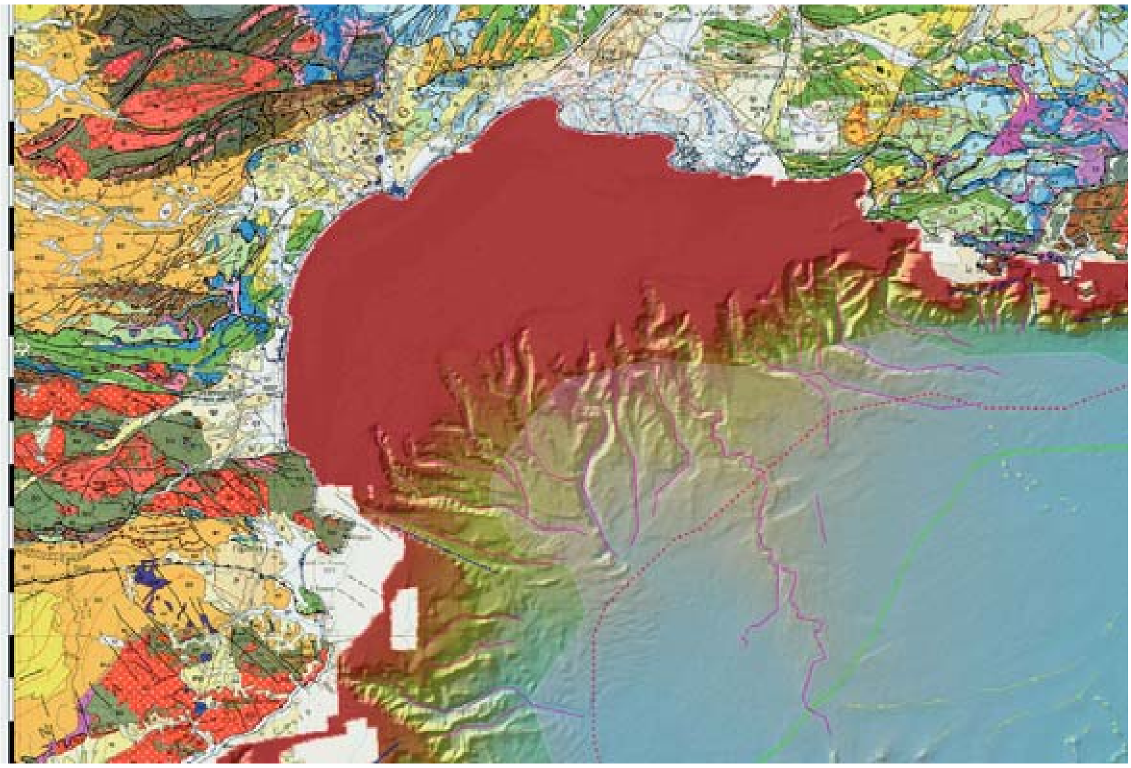


Figure 6. The main canyons of the Gulf of Lion (DTM at 500 m from swath bathymetric data).

These canyons are covered by hemipelagic muddy sediments and entail thick Pliocene and Quaternary sediments (Fig. 7 a and b) deposited though times on the wide continental platform by bordering rivers, particularly the Rhone.

(a) (b)

Figure 7: Submarine views within two of the Gulf of Lion canyons: (a) recent burrowed soft sediments in Sète canyon; (b) semi-indurated Pliocene (?) marls in Montpellier canyon (Documents from the AAMP [1] Medseacan surveys).

A dense network of seismic data recorded across the Gulf of Lion platform has demonstrated that most of these recent "*sedimentary*"-type canyons are however superimposed on former sub-

[1] AAMP is the acronym of the French Agency on MPAs.

aerial/valleys created during Messinian times (roughly between 6 and 5 My ago), when the sea level dropped drastically (perhaps on the order of 1200/1500 m). Further east, from Marseille to Genova, almost all canyons are clearly matching former geological units and/or tectonic trends and have been strongly reshaped, at least in their upper courses, with aerial erosion operating on the area during the Messinian low stand. These features cut across various geological formations, made either of massive limestone (east of Marseille), metamorphic and volcanic rocks (from Toulon to Fréjus), alpine-derived units and coarse Pliocene conglomerates (from Cannes to Genova) often directly exposed at the seabed (Fig. 8a).

Figure 8: submarine views within two rocky canyons: (a) probable Pliocene conglomerate in the Var canyon; (b) metamorphic rocks in the Valinco canyon (Documents from the AAMP Medseacan surveys).

A comparable setting characterizes the western Corsica margin (Fig. 8b) and likely the western continental slope off Sardinia, where the effects of Messinian erosion may also have been superimposed on previous submarine valleys and canyons created at the origin of the Western Mediterranean basin.

Except in certain areas off Sardinia (Gamberi, this volume), Northern Sicily (Lo Iaconno *et al.*, this volume) and western Calabria (Ceramicola *et al.*, this volume) no large canyons can be seen around the Tyrrhenian Sea (Chiocci, this volume); this is likely a consequence of the very recent age of this basin created in the last 7 my, for its western border, and only in the last 3 to 2 my for its southern corner, and whose continental slopes have therefore been little affected by submarine deposition and erosion so far. Only short, often sub-linear, canyons or gulleys cut into the narrow, tectonically active and uplifting continental slopes along the North African margins, where moreover the drainage pattern consists of short-lived rivers without sustainable water supply. A comparable setting prevails along the Alboran Sea northern margin where strong deep currents play an important role in sediment dispersion (Vázquez *et al.*, this volume).

- ***Eastern Mediterranean and Black Seas***

Around the Eastern Mediterranean basins (Fig. 9), only eastern Calabria, Cyrenaica and Western desert (Western Egypt) continental slopes show significant canyon networks.

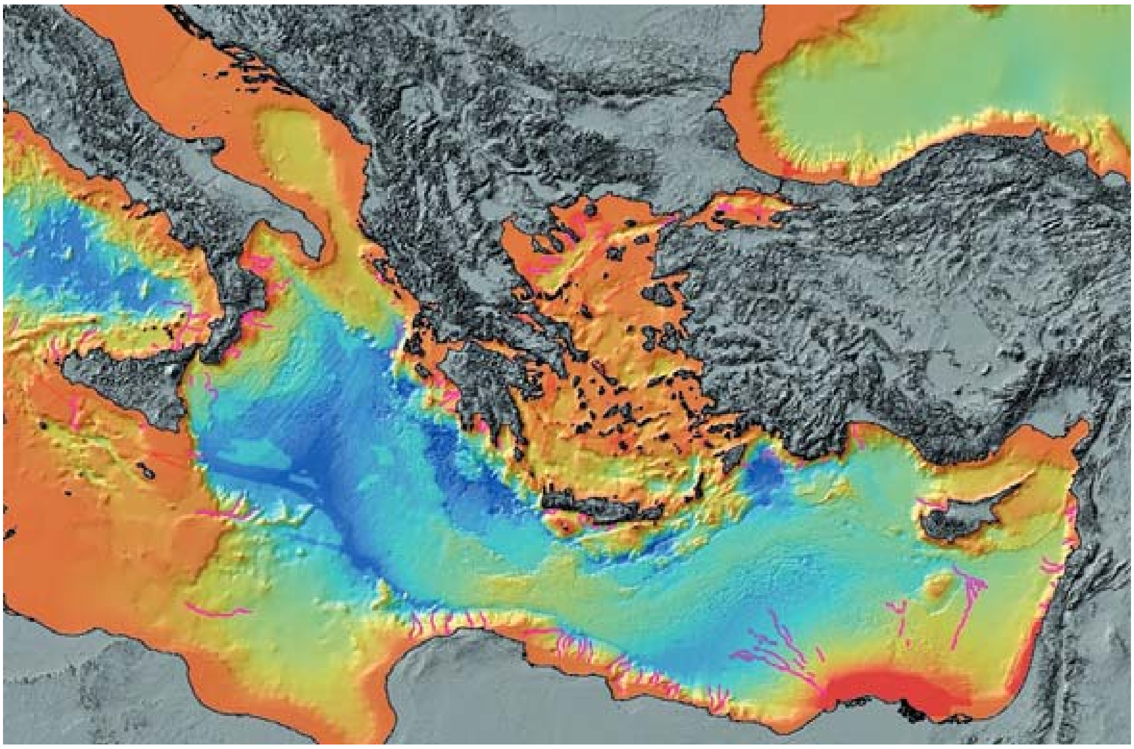


Figure 9. The main estern Mediterranean Sea canyons systems (in purple) (after Migeon *et al.,* 2012).

Off Calabria most of the canyons appear directly connected to short mountain-supplied rivers as a consequence of a general, and still active, coastal uplift (Ceramicola *et al.*, this volume). Only a few significant canyons can be observed West of the Peloponnese, South of Crete and south of Turkey as well as off the Levantine coast. Little is known on these features, which are all located on active tectonic zones. Relatively short canyons can be seen off Cyrenaica and the Western desert. These features, possibly rejuvenated during the Messinian low stand, are not anymore connected with any aerial drainage system and probably did not evolve since that time, except may be during Quaternary pluvial periods. Off the Nile delta only one single and large canyon exists today: extending just at the mouth of the Rosetta branch of the Nile River (Fig. 9). The Rosetta canyon, feeds a complex meandering channel system through which most of the erosion products from the Nile River are dispersed into the northern bordering deep abyssal plain. With the exception of a few short canyons in tectonically active areas, such as in the Marmara Sea (Çağatay *et al.*, this volume) and near the North Anatolia trough (North Aegean), no significant canyon can be observed within the very shallow Aegean Sea, which is a very shallow domain. Finally several important canyons characterize the Black Sea along both its Southern and Northeastern shores and particularly along its Western shelf and slope where the Danube connects, across a wide sedimented platform, with a sinuous canyon itself connecting to a channel and levee system (Popescu *et al.*, this volume).

Two case studies

- *Northern Liguria/Corsica margin canyon systems*

Along the Riviera and Liguria margins, the continental shelf is very narrow, ranging from a maximum of 2 km to less than 200 m (in front of Nice airport). On average the shelf break is always quite close from the coasts and lies at an average water depth around 50-100 m; it may even be shallower and is found at than 20 m in front of Nice airport (Dan *et al.*, 2007). Based on its morphological characteristics the Liguria margin can be divided in a western and an eastern segments, separated by a SW-NE trending ridge or Imperia promontory (Larroque *et al.*, 2011). From Nice to the Gulf of Genova (Fig. 3) seventeen canyons can be detected. These canyons initiate either at shallow water depth, directly at the mouth of rivers feeding the Liguria/Riviera continental slope and basin (Var, Paillon, Roya, Nervia Argentina rivers), or along the outer continental shelf; sometimes these canyons may even have initiated at greater depth directly on the upper continental slope. All along the two segments the continental slope appears quite steep (average angle of 11°) and reaches, in less than 20 km, water depths of more than 2000 m (Cochonat *et al.*, 1993). Such marked steepness in the continental slope, which allows the observation of outcrops (see Fig. 8a), is a direct consequence of tectonic inversion processes in progress leading to the remobilization of former transverse lineaments and even to the creation of new fault zones, particularly at the foot of the margin (Béthoux *et al.*, 1992; Larroque *et al.*, 2009). One consequence of such new tectonic activity is a regional uplift (Bigot-Cormier *et al.*, 2004; Sage *et al.*, 2011), which in turn leads to enhancements of sedimentary gravity flow and mass wasting processes, including directly in some canyons. Along the western coast of Corsica the quasi absence of erosion-derived supplies, except by potential flash flows, has prevented most of the canyons to be fed by significant sedimentary cover at least in their upper thalweg; it is therefore possible to directly observe, during deep dives, exposed basement rocks, such as granite, volcanic, metamorphic units (see Fig. 8b), in which these canyons – as aerial valleys during the Messinian – low stand, were likely created as a consequence of the rifting of the Ligurian basin during Miocene.

- The Nile canyon

By far the Nile deep-sea cone (Fig. 10) today represents the largest Plio-Quaternary clastic accumulation of the Mediterranean Sea (Bellaiche *et al.*, 1999).

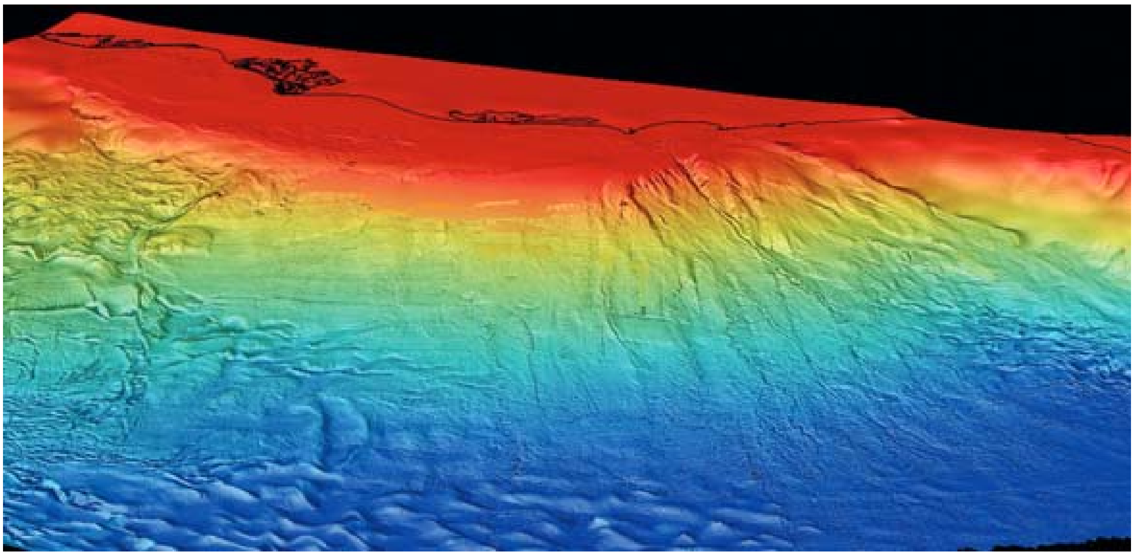


Figure 10. 3D view (from North) of the Nile cone (based on a DTM at 100 m); the Rosetta canyon (to the right just at the mouth of the Nile Rosetta branch), is today the only active canyon through which erosion-derived sediments are transported and delivered to the continental slope and deep abyssal plain.

At least since Messinian times (6my ago) the Nile River has continuously delivered sediments to the deep Herodotus abyssal plain thanks to various networks of canyons and channels that have continuously evolved through Pliocene and Quaternary times (Ducassou *et al.*, 2009). This has resulted in the construction of an approximately 2000-2500 m thick Pliocene and Quaternary sedimentary bulge, the present-day Nile deep-sea cone (Loncke, 2002). Among the four distinct morpho-structural provinces that have been recognized on morphologic grounds (Loncke *et al.*, 2002) only the western one today shows a long and wide canyon, the Rosetta canyon, extending just at the mouth of the Rosetta branch of the Nile (Garziglia *et al.*, 2008) (Fig. 11).

At the present highstand of sea level, particles delivered by the Nile River are deposited on the continental shelf and along the coast due to a westward coastal current and on the continental slope. During the last sea-level lowstand and wet event above the Nile River sources, a connection between the river and the canyon was established and the Rosetta Canyon served as the main conduit for the delivery of high amounts of particles to the deep basin.

On the continental slope a complex network of at least four channel-levee systems shows a westward migration in time. According to Garziglia *et al.* (2008) and Rouillard (2010) such migration seems to have been controlled by interconnected plays of three distinct mechanisms:

(a) Quaternary climatic fluctuations (Ducassou *et al.*, 2009) and particularly monsoon variations (Revel *et al.*, 2010 and 2014) ***(b)*** large and repeated submarine landslides that have affected the upper continental slope (Garziglia *et al.*, 2008), and ***(c)*** frequent modifications in the location of various feeding canyons, which were apparently buried and reworked for some of them by repeated mass-wasting events (Rouillard, 2010).

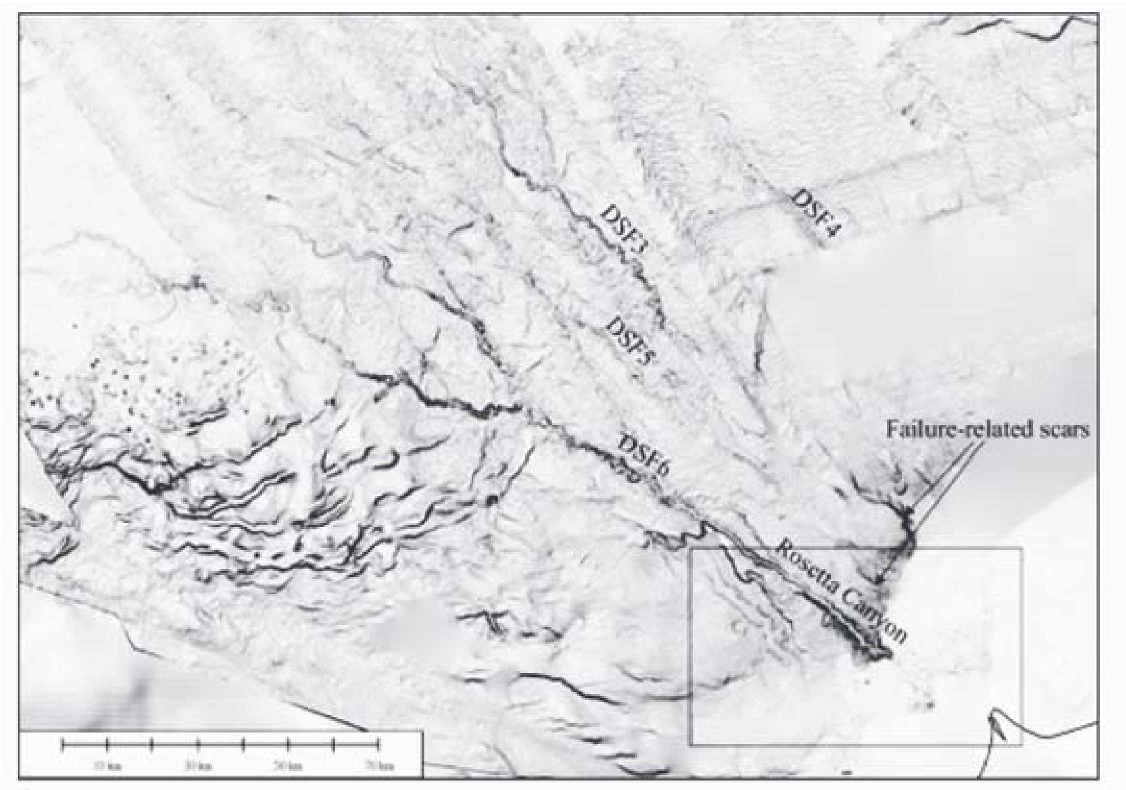


Figure 11. Rosetta canyon initiates, at only 70m water depth, on the continental shelf just northwest of the Rosetta branch of the Nile (see within the rectangle). The canyon is cut in an area submitted to numerous mass-wasting processes, which have disconnected Quaternary canyons “ancestors” from previous channel-levee systems. The current canyon connects with DSF6, the last channel-system through which sediments are directly transported to the lower slope and abyssal plain.

The most recent deep channel levee system is clearly directly connected to the Rosetta Canyon, which initiates on the outer continental shelf by only 70 m water depth, at about 30 km off the Nile Rosetta branch. The canyon, whose shallow head displays a typical amphitheater-like morphology resulting from repeated mass wasting, is about 25 km long, 200-250 m deep and progressively narrows from 8 to 5 km downslope. 2D and 3D seismic reflection data tied to petroleum wells on the continental shelf have allowed to identify nine other buried canyons in the area characterized by various sizes, shapes, sinuosity, and lengths of shelf incision and built since the Upper Pliocene (Rouillard, 2010) (Fig. 12). Three canyons have very likely been formed during the last 120 ky feeding and the Rosetta Canyon was likely formed only about 50 ky ago. We estimate that late Quaternary canyons have a period of activity in the order of 40 ka.

Canyons formed before the beginning of Quaternary climato-eustatic variations (1,8 My ago) clearly show larger dimensions with longer incisions in the continental shelf and more complex infilling, suggesting longer time of activity due to different conditions in sediment supply and climate on Nile sources, in tectonic regime on the margin and in global eustatism (Rouillard, 2010).

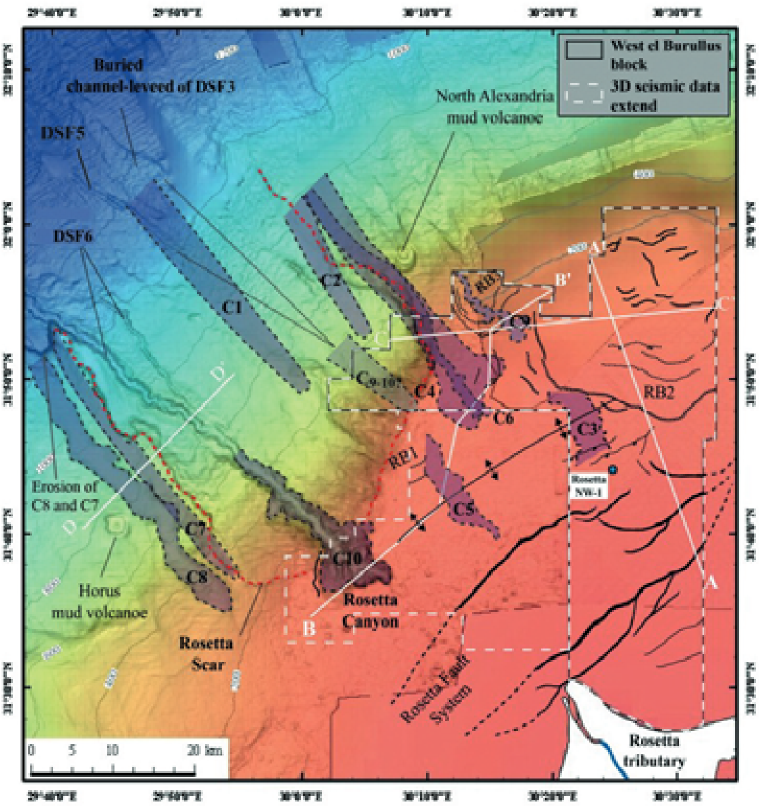


Figure 12. Rosetta canyon (C10) and its various Quaternary « ancestors » as detected from 3D seismic data (Rouillard, 2010).

We suspect that these canyons, whose period of activity is in the order of 35-40 ka, result from different processes of formation and evolution.

Conclusions

From this brief survey of the main Mediterranean canyon systems, and from the short presentations of two case studies, we may conclude the following:

- ***(1)*** Like for most of the rivers, a large majority of Mediterranean canyons are superimposed on lines of weakness, themselves consequences of past or recent tectonic activities. These tectonically controlled lineaments are derived either from previous regional geological evolution (Alps chains for example in the case of the Riviera/Liguria margin), or are directly inherited from various rifting episods that have created, and shaped, the western Mediterranean Sea margins between Upper Oligocene and Miocene (from eastern Spain to western Sardinia), during late Miocene and Pliocene (eastern Sardinia, northern Sicily, western Calabria), or possibly before, as far as early Mesozoic (for example along the Libya Margin). This geodynamic control has often led to create canyons, which are now mature and in which gravity flow and mass wasting processes were and are prevailing. Much younger, and less mature canyons, may, however, also be closely controlled by tectonics occuring either on active continental margin segments (such as Southern Calabria, Western Peloponnese), simply tectonically active area (Marmara Sea) or slope segments, which are progressively tectonically reactivated (e.g. central Liguria margin, Algeria, Cyprus, Crete margins).

- ***(2)*** In western Mediterranean Sea particularly the upper part of thalwegs of most canyons appears to have been deeply entailed or re-shaped under aerial to sub-aerial conditions. During the Messinian time span (roughly between 6 to 5 My ago) the sea level may have dropped by several hundred meters (possibly up to 1.5 km) below the present day level and such conditions have led to aerial expositions of many of the upper continental slope segments. The Messinian event constitutes therefore an important specificity which has strongly impacted the evolution of many Mediterranean canyons. As a consequence of this aerial erosion, canyons walls often show rock outcrops directly exposed on the seafloor. These features constitute what we propose to distinguish as « rocky » canyons. Such rocky canyons, cutting directly accross indurated geological units, may however also characterize areas where tectonic and uplift are still active (or have recently been active) and where the sedimentary supply remains very low. (e.g. Southern Calabria, Algeria).

- ***(3)*** In contrast to the majority of canyons, the Ebro, Rhone, Nile, Danube canyon systems and, at some stage, smaller river-linked canyons (such as the Var) and their related long and sinuous channel/levee systems run and cut across thickly sedimented platforms and gentle continental slopes. By opposition to « rocky » canyons we propose to term these features « sedimentary » canyons. Even if these canyons are mainly controlled by interconnected mechanisms such as climatic and/or eustatic fluctuations (e.g. Rhone, western Nile canyons), dense flows and mass wasting processes, their location may have been influenced by preexisting subaerial valleys (e.g. Gulf of Lion) inherited from the Mediterranean specific Messinian event and/or from previous tectonic controls.

Acknowledgments

Thanks to all colleagues (onboard crews, technicians, scientists) who participated to the acquisition, processing and interpretation of the data shown and discussed in this paper.

---

* this chapter is to be cited as:

Mascle J., Migeon S., Coste M., Hassoun V., Rouillard P. 2015. “Rocky” versus “Sedimentary” canyons around the Mediterranean and the Black seas. pp. 37 - 48 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.

Canyon comparison as a key to constrain some scientific problem about their geology

Francesco L. Chiocci

Department of Earth Sciences, University of Rome Sapienza, Italy

INTRODUCTION

Since the pioneering studies of Francis P. Shepard, submarine canyons have attracted the attention of marine geologists as very spectacular, singular and relevant element of continental margins. They are in fact extremely relevant in many respects: pathway of shelf pollutants to the low-resilience deep water environment, site of upwelling/downwelling oceanographic processes, hotspot for biodiversity, route for turbidity current feeding deep sea fan and turbiditic complexes, finally one of the most prominent geohazard feature in the marine environment.

Although they represent one of the more attractive and best studied geological features of the seafloor, still many question remain unanswered. How do they form? Why do they form? How do they evolve?
Are they linked to the erosional activity of rivers during sea level lows (as can be the case of the Mediterranean during Messinian time) or are they independent from subaerial watercourses (as can be again the case of the Mediterranean where most of the canyons are located in front of small streams or where no watercourses exist)?
Are they evolving retrogressively from a self- organisation of widespread mass- wasting of the slope or are the hyperpycnal flows from the coast/shelf the key morphogenetic factor? What is their relation with faults and tectonic features? Why are some meandering and others straight? Why will in some case two canyons run parallel to each other without connecting for tens of kilometres?
Technological advances continuously offer new data and interpretative hints to the research community such as multibeam bathymetry, data from seafloor observatories, 3D seismics and high- resolution oceanographic modelling, but the episodic nature of some processes and the difficulty to navigate the canyons (for instance with AUV or deep tow instruments) still leave many aspects to be completely understood.

Therefore constraints, if not answers, may arise from comparing different canyons in different geological/geodynamic/physiographic setting in regions where canyons are common and a full coverage of multibeam bathymetry allows for a complete and detailed comparative geomorphologic analysis. Such a region is Italy, where the MaGIC (MArine Geohazard along the Italian Coast) project was realised in recent years, funded with 5.25 M€ by the National Civil Defense Department.

The project involved the whole Italian marine geology scientific community (three CNR institutes, seven universities, OGS- Trieste) and provided 73 sheets of the "Map of Geohazard Features of the Italian Seas" plus a web- GIS database (Infor.Mare) to retrieve in real time all the maps present in scientific literature dealing with the marine geology of the Italian Seas.

Some 39,000 nautical miles of multibeam data have been acquired and integrated with 10,000 from previous surveys. Almost 2/3 of the Italian coasts have been covered by the project as we excluded shallow epicontinental seas (e.g. Northern- central Adriatic, northern Tyrrhenian, Sicily Channel) as in general they host few geohazard features (Fig. 1). The depth range we investigated is 50- 1000m w.d. even if we reached shallower water at canyon head or everywhere needed and we stopped deeper (80- 90m) where wide shelves were present. The setting- up of common procedures for data acquisition, processing, interpretation and cartographic representation has been complex and reiterative due to the need of having standard methods suitable for the different realms (shelf to slope, volcanic/rocky to sedimentary- covered seafloor, erosion dominated to deposition dominated environments, …) and trying to differentiate between morphological (objective) and genetic (interpretative) representation of the depicted features.

The target was achieved by the establishment of a complex and comprehensive nomenclature and legend, a four level of interpretation and cartographic representation, ranging in scale from 1:250.000 to 50.000 (mainly) and up to more detailed scales for specific points of interest.

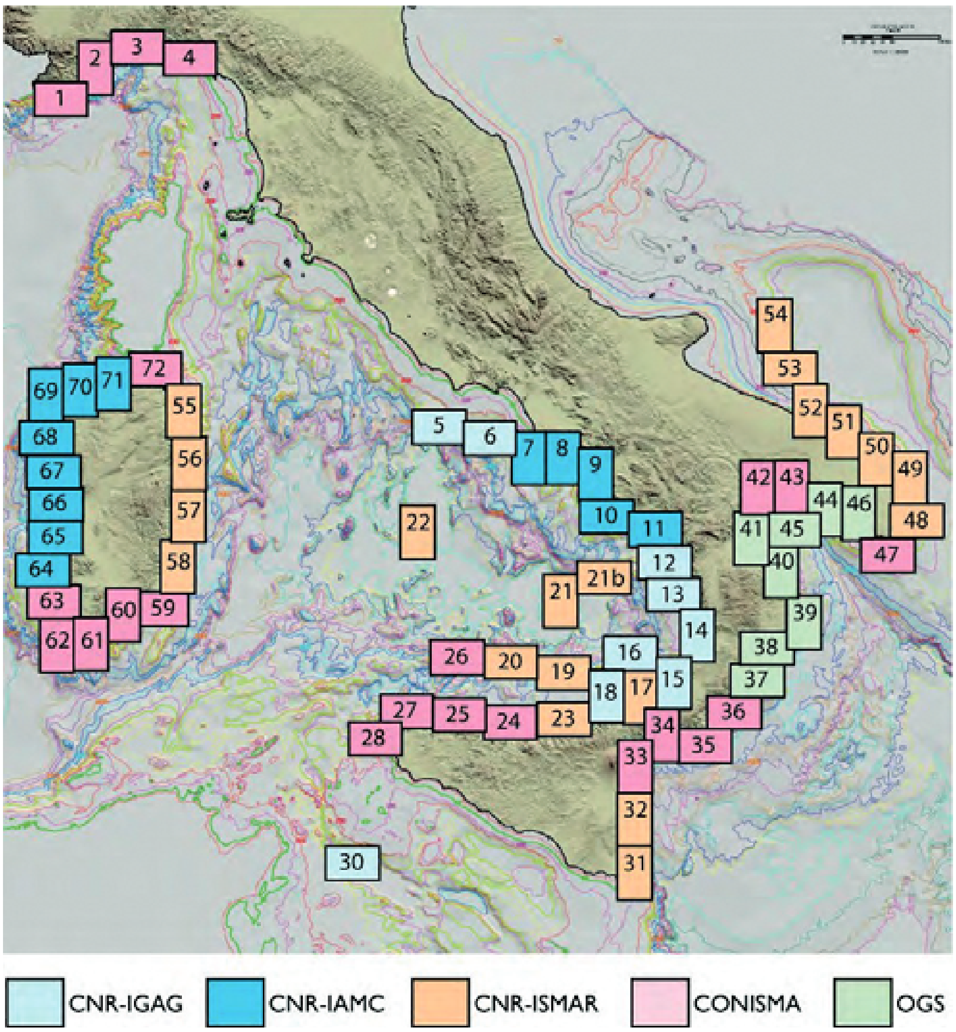


Figure 1. Location map of the 72 sheets produced by Magic Project. The areas studied are fully covered by multibeam data with enhanced geomorphological interpretation aimed at defining geohazard features on continental margin, canyons among the first. Colours indicate the institutes responsible for data acquisition and interpretation.

Therefore, thanks to the Magic project, a detailed and continuous multibeam mapping is now available all along the investigated Italian continental margins, whose geology is as varied as that of coastal domains (see Fig. 2). The Adriatic 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; the Ionian Sea is a relict of 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 both to west (Sardinia) and to the East (Campania), both 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.

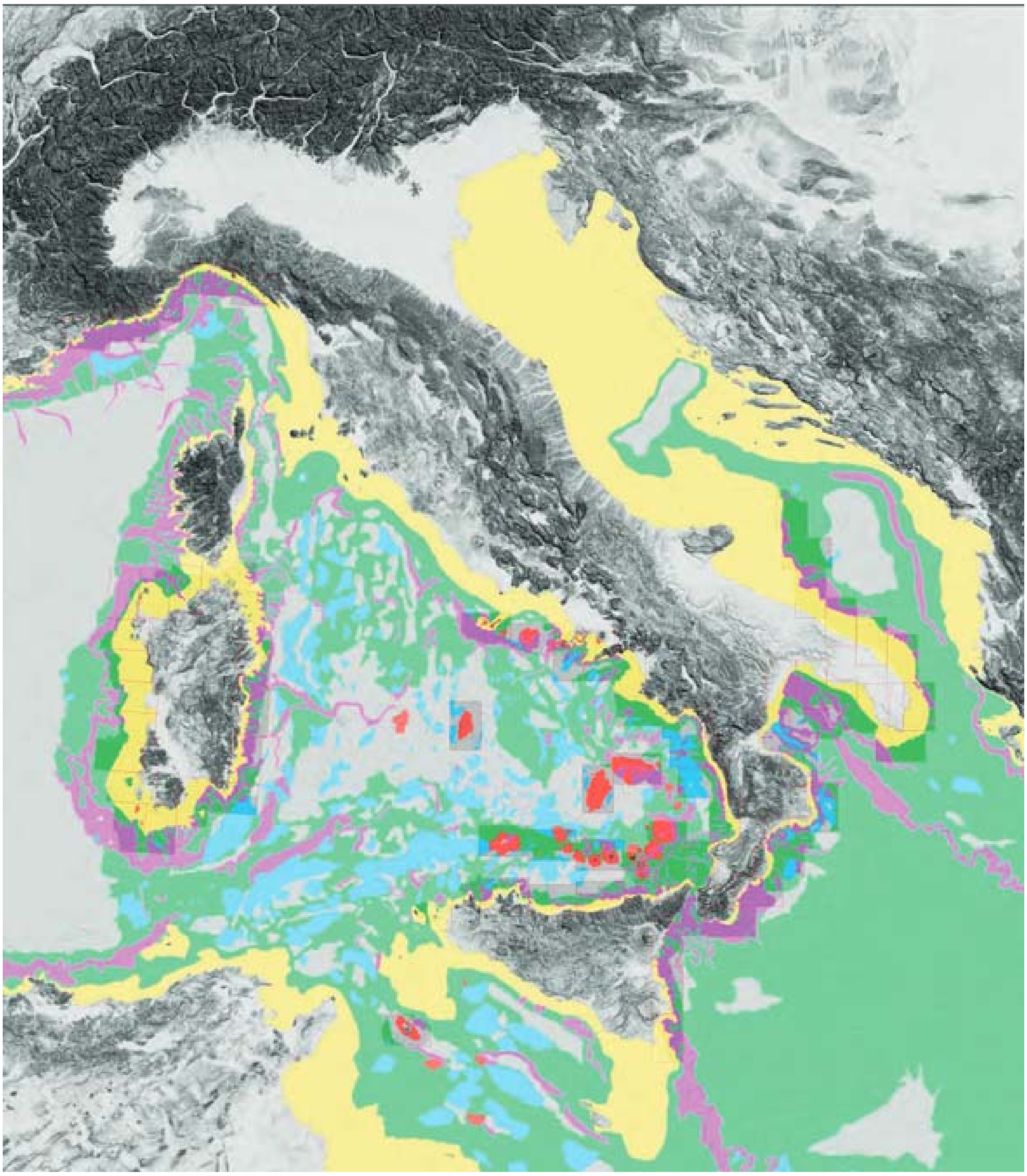


Figure 2. Physiographic chart of the Italian Seas, after Magic Project. Canyons and erosional areas are in purple.

By comparing this setting we may try to answer scientific question such as:

1) Why are canyons in the western Tyrrhenian Sea only present in the Gulf of Naples, in Calabria and in Liguria?

For the latter two the short torrential stream with steep basin located in the mountain range close to the coast, the Quaternary tectonic uplift, the lack of continental shelf and the seismicity may account for high sedimentation rate on the slope. But in the Gulf of Naples none of the above factors is present. Instead huge explosive volcanic eruptions occurred there, with possible huge input of volcanoclastic sediments to the margin, fed by the activity of Campi Flegrei volcano at first and later by Vesuvio and Roccamonfina volcanoes.

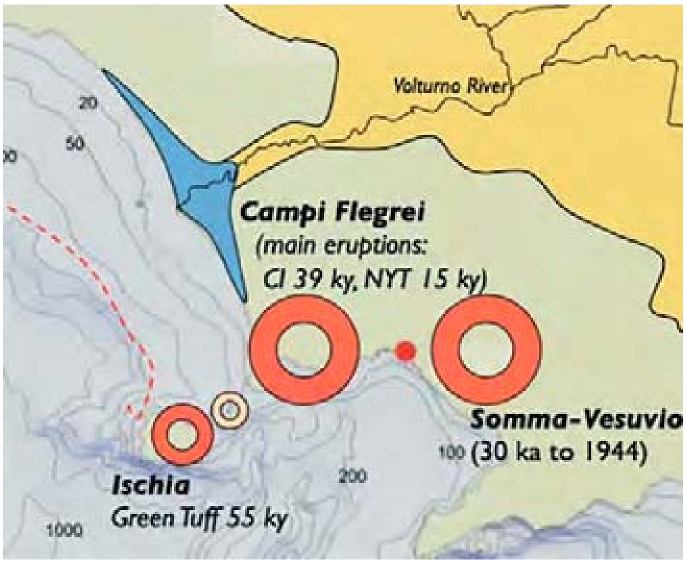


Figure 3. The area around the Gulf of Naples is dominated by active volcanoes; especially Campi Flegrei produced a huge amount of pyroclast due to two main explosive eruptions of Ignimbrite Campana (IC) and Neapolitan Yellow Tuff (NYT), whose age is indicated.

We therefore hypothesize that high sedimentation rate of volcanoclastic material is responsible for the presence of canyons that were the conduit from where a huge amount of sediment was evacuated from the coastal area, the (at that time subaerially exposed) continental shelf and the Volturno River drainage basin (Fig. 3). Therefore the age of main explosive eruptions (Napolitan Yellow Tuff and Campanian Ignimbrite, 15 and 39 kyr BP, respectively) constrain the age and the rate of canyon formation.

Moreover the Cuma canyon running north of Ischia has been partially dismantled by the activity of debris flows due to the resurgence of the Monte Epomeo in Ischia.

Similarly the Magnaghi canyon running just south of Ischia Island, has been completely filled up and erased by a huge debris avalanche created by the same resurgence. As Monte Epomeo is the infilling of a caldera formed just some 5000 years BP, the case of the Gulf of Naples demonstrates how fast canyons can be to created and dismantled.

2) Why in the Ionian and Tyrrhenian sea the two sides of the Calabrian Arc show completely different canyon systems?

Both sides are similar in terms of bedrock geology, tectonics, climate but the canyon pattern and character is strikingly different. In the Tyrrhenian they are few, extremely long and not correlated at all with main watercourses; they often show rejuvenation processes or change in the course due to tectonic movement on the slope (Fig. 4). To the contrary on the Ionian side of Calabria they are many and closely spaced, often located in front of small stream mouths. They show multiple and complex heads that collect and connect many incisions in the upper slope.

The occurrence of very different canyon patterns in two regions points out a close connection of overall drainage pattern of the margin with the geodynamic realm of the two sides of the arc. In the western young backarc Tyrrhenian basin, where tectonic movements are fast and very variable in a short time, the presence of subsiding sectors of the margin and intraslope basin trapped the gravity flows and hinders the formation of a large network of canyon; only few long canyons developed. In the eastern Ionian forearc basin the high sedimentation rate, the older age and the relatively constant tectonic regime caused the formation of a widespread network of canyons that carve the whole margin.

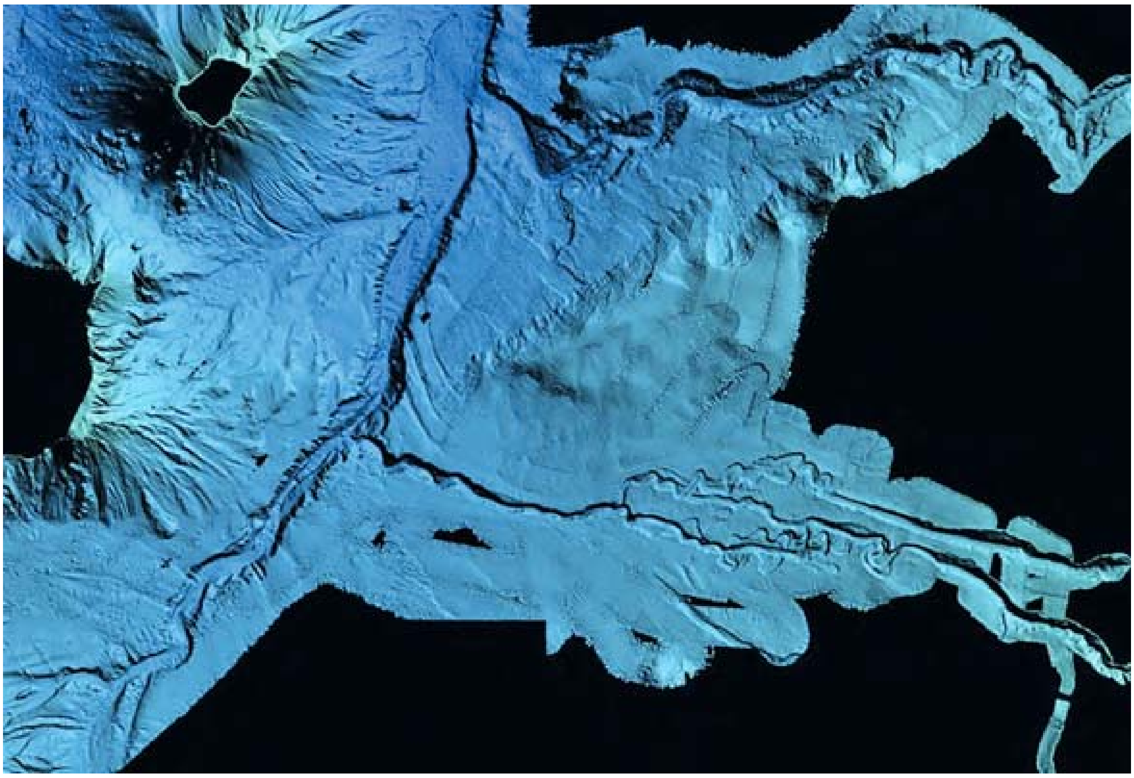


Figure 4. Gioia Mesima canyons (to the south) and Angitola canyon (to the north), both reaching the Stromboli Canyon (to the west) in the south-eastern Tyrrhenian Sea. Here tectonic movements occurring on the slope control the canyon geometry.

3) Is the canyon head inherently representing a geohazard?

The answer appears to be positive either in the long- and short- term.
In the Mediterranean, Nice 1979 and Gioia Tauro 1977 are two examples of very similar small failures (few millions of cubic meters) at canyon head that caused several meters- high tsunami waves and in Nice also several casualties. This is a well known geohazard that is particularly

relevant in the Mediterranean region where the risk connected to landslide- generated tsunamis is very high not negligible in respect to the earthquake- generated tsunamis. In fact for the latter, the seismic magnitude does not exceed 7.5 and the short distances does not allow for early- warning systems (as the Pacific DART) to be deployed. Landslide- generated tsunamis may be far more frequent in geologically active regions even if such events may have not been recorded in the historical record because of the small extent of the coastal area affected and because they mainly occur on rocky shores that were remote and hardly inhabited before the last century. Nowadays previously remote rocky coasts are heavily exploited for tourism in many parts of France, Italy, Greece, Turkey.

In several cases failure at canyon head is known for occured but involving smaller volume of rocks or with different failure modes, and so without producing tsunami waves. Canyon heads are inherently unstable and subject to fail as canyons naturally evolve by retrogression of their head. We may assume that canyon heads will sooner or later inevitably reach the coast and affect the stability of the subaerial slope. If one observes the characters of a rocky coast close to a canyon head, one will often note a sharp coincidence between canyon head and coastal morphology (see following Figures 5 to 8).

Figure 5. Aerial photo (after Google Earth) of Ognina (north of Catania), Vulcano Island (Eolian archipelago) and Reggio Calabria coast (Messina Strait). White bar =1km. The morphology of the coast is strictly controlled by canyon head location and activity at different scale.

Figure 6. Ognina coast. The Catania canyon head reaches the coast, unbuttressing the lava flows and impacting nearshore facies. Azimuthal aerial photo of the coast in Fig. 5.

Figure 7. Eastern coast of Lipari Island, here the morphology is controlled at different scale by the presence of canyon heads. They are responsible for the large gulf north and south the Monterosa headland (at the centre of the image) and the small embayments on the southern part of the island. aerial photo of the coast in Fig. 5.

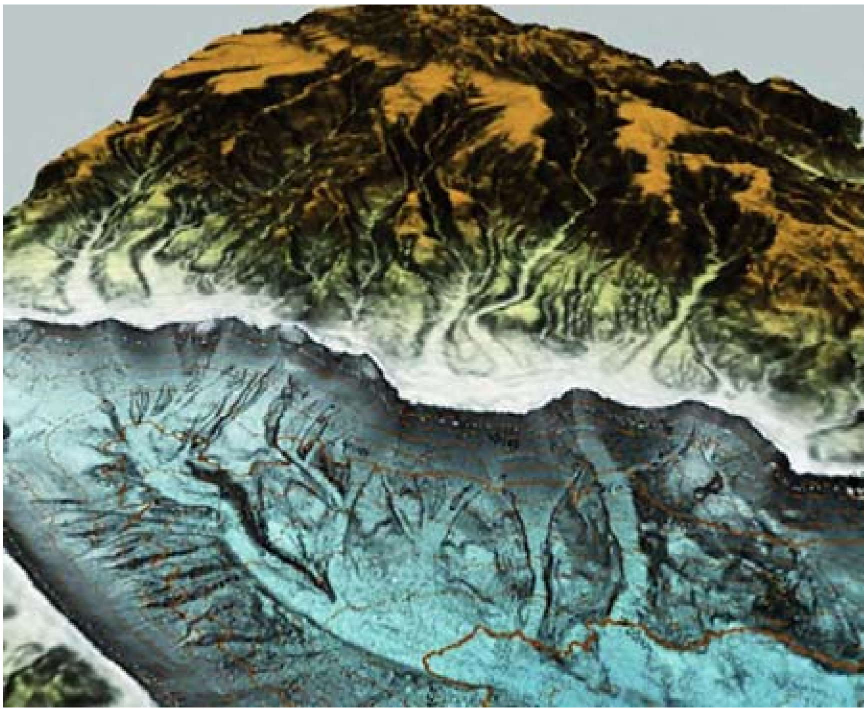


Figure 8. 3D view of the eastern side of the Messina strait. The left tributaries of Messinia canyon carves the slope and match the coastal morphology. In this case an interplay exists between erosional activity of canyons and constructional activity of fan deltas fed by streams on the coast. Azimuthal aerial photo of the coast in Fig. 5.

It is therefore reasonable to interpret the coastal morphology as the result of recent (?) coastal landslides that shaped the coast because of canyon head unbutressing of the cliff. Is it possible therefore to exclude geohazard potential for those canyon heads that show no morphological correspondence with the coast? Where there is correspondence but canyon head are nowadays far from the cliff, this fact may indicate phases of erosion and infilling (possibly driven by glacio-eustatic changes) so that canyon are undergoing a period of relative quiescence.

4) Finally (but this is not an exhaustive list) *why many canyon are located exactly in front of main harbours, so bearing an extremely high hazard for direct (landslide) or indirect (tsunami) destruction of such important infrastructures:*

Consider Gioia Tauro, for instance (Fig. 9). It is today the main transhipment port of the whole Mediterranean, one of the main entry point for Civil Protection during possible emergency due to strong earthquake in southern Italy and its entrance is located exactly in front of one of the 4- 5 canyon heads of the 300 km long Tyrrhenian coast of Calabria. This situation is not uncommon for other canyons. Is this just an unfortunate coincidence? One may argue that a complex interplay between submarine geomorphology, oceanographic processes and societal development does account for such a setting. In fact is it possible that wave refraction let the coast onshore canyon head be characterised by a lower height of storm wave and therefore be the most suitable landing site for small fishing boats. Such situation may have favoured the development of coastal villages, then towns, then cities with the need of building harbours in places that were the most favourable for small boats but the most disadvantageous for large infrastructures. This is the case of Cirò Marina harbour and canyon where the development of coastal infrastructures caused a shift between favourable/unfavourable conditions, so that a recently built new harbour had to be closed for damages just a few years after the inauguration (Fig. 10).

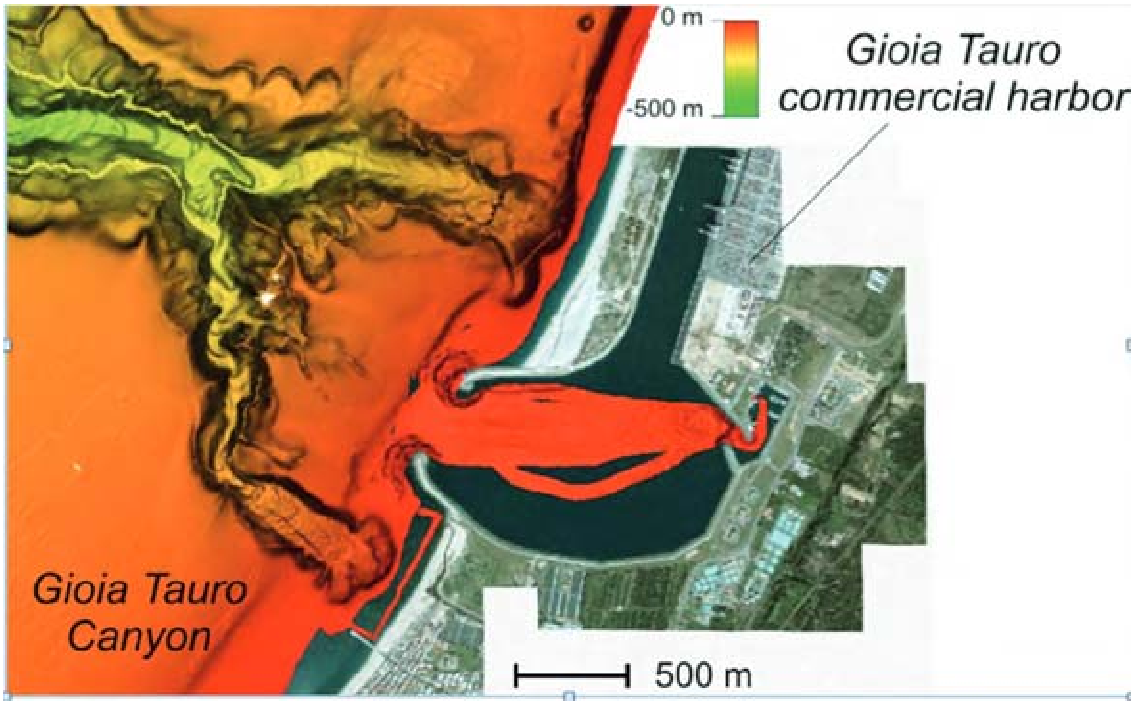


Figure 9. The head of Gioia Tauro canyon is located a few hundreds meters from the entrance of Gioia Tauro harbour, the main transhipment harbour of the Mediterranean. Here in 1977 a tsunamogenic landslide occurred during pier construction.

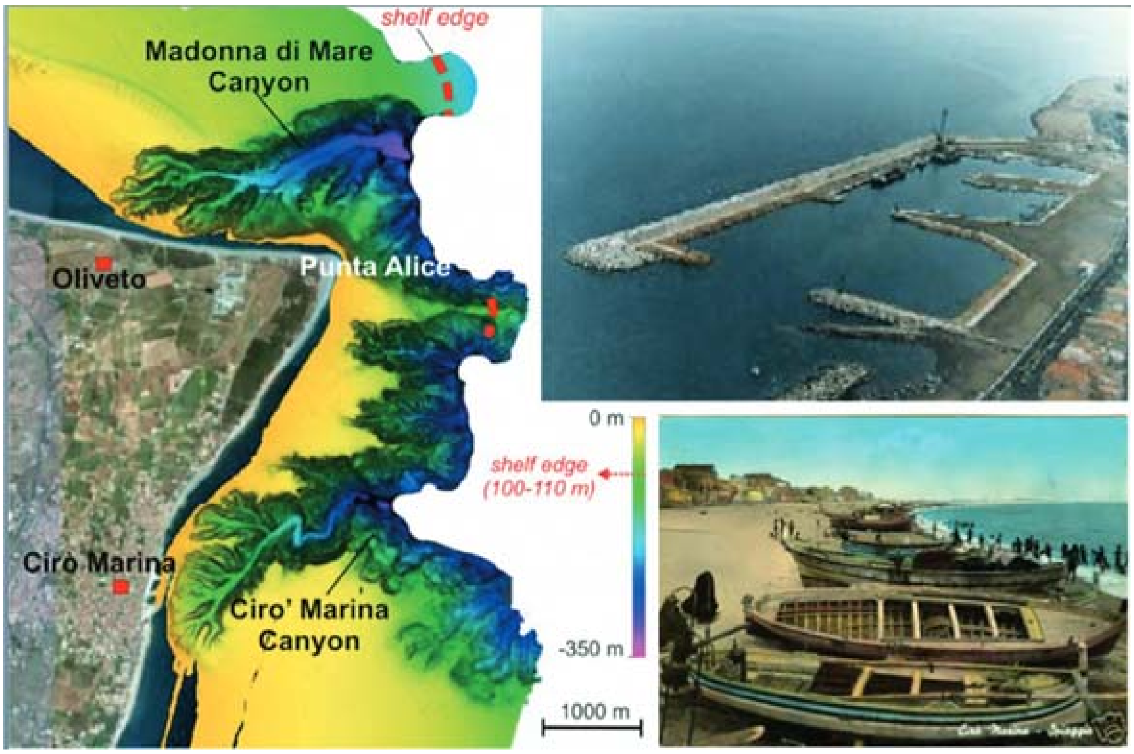


Figure 10. Cirò marina canyon head affects the outer part of the harbour (upper right). Cirò Marina nowadays is a rather large town but in the past was a fisherman village where small boats were landing on the beach (lower right).

* this chapter is to be cited as:

Chiocci F.L. 2015. Canyon comparison as a key to constrain some scientific problem about their geology. pp. 49 - 58 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.

Interaction of large landslides and canyons off NW-Africa

Sebastian Krastel

Institute for Geosciences, Kiel University, Germany

Abstract

Landslides are important during the evolution of canyons. The origin of many canyons is due to mass wasting events and subsequent headward erosion. Failures of canyon walls are important for shaping the morphology of canyons. Such failures are usually relatively small. Another type of interaction may occur if large landslides on the open slope occur in close vicinity to canyons. This type of interaction can be well investigated at the NW-African continental margin, which is characterized by abundant canyons and gullies as well as large but infrequent mass wasting events. Major canyons at the NW-African continental margin include the Dakar Canyon off Senegal, the Cap Timiris Canyon off Mauritania and the Agadir Canyon off Morocco. Giant landslide preferably occur in areas which do not show a large concentration of canyons and gullies. These areas allow the accumulation of thick sedimentary successions which may fail and form large-scale landslides. Most of the landslides interact with nearby canyons at the lower slope or continental rise because the landslides spread over larger areas and occasionally hit the canyons. We observe different behaviors for this type of interaction between canyons and landslides. The Dakar Slide off Senegal destroys the Dakar Canyon, which is ‘only’ about 75 m deep at this location and not protected by a well-developed levee. This destruction leads to a reorganization of sediment transport processes in Dakar Canyon. A similar setting of a giant landslide (Cap Blanc Landslide) and canyon (Cap Timiris Canyon) is found off Mauritania. The Cap Timiris Canyon, however, is protected by a very well developed levee and the landslide did not enter the canyon. The Agadir Landslide enters Agadir Canyon off Morocco but the canyon is still about 500 m deep at this location. Hence, it does not change canyon morphology significantly.

Introduction

Gravity driven sediment transport is widespread on all types of continental margins; it may occur in canyons and channels as well as on the open slope. Submarine canyons are major incisions at continental margins around the world (Harris and Whiteway, 2011). The origin of canyons may be caused by mass wasting events at a mid slope locations and subsequent headward erosion or by downslope traveling sediment-laden gravity flows, so-called turbidity currents (Daly, 1936; Twichell and Roberts, 1982; Pratson and Coakley, 1996; Harris and Macmillan-Lawler, this volume). A combination of both processes (downslope and upslope erosion) is also suggested by several authors (e.g., Pratson and Coakley, 1996).

Canyons represent a highly dynamic environment due to passing tidal and turbidity currents, forming complex sea floor features (Huvenne and Davies, 2014 and references therein). They represent important pathways for transportation of sediment from the shelf into the deep sea

(Damuth, 1994; Bouma, 2001; de Stiger *et al.*, 2007; Galy *et al.*, 2007). Often steep canyon walls become unstable and fall into the canyons thereby introducing slide/slump and debris flow material, which is incorporated into the canyon mainstream for downslope transport. This process is the most common cause of canyon widening (Posamentier, 2003). Canyons may evolve into channels, which are bounded by depositional levees (Imran *et al.*, 1998).

Submarine landslides occur on continental margins worldwide. Landslide processes on continental margins include translational sliding, rotational slumps, and debris flows. Debris avalanches are widespread on the flanks of volcanic islands. The size of submarine landslides varies over several orders of magnitude; they may be very large with volumes of several 1000s of km^3 and runout distances of up to 900 km (Nisbet and Piper, 1998). The largest landslides are found on passive margins. Active margins are characterized by a large number of small events and a small number of large events. This distribution is probably linked to a power-law distribution of trigger mechanisms, such as earthquakes that destabilize quickly accumulated marine sediments (Yamada *et al.*, 2010). Landslides and sediment gravity flows are also a significant geohazard to seafloor infrastructure, e.g. pipelines and telecommunications cables and some have generated tsunamis (Tappin *et al.*, 2001; Bondevik *et al.*, 2005).

It is well known that submarine landslides do play an important role during canyon evolution (Micallef *et al.*, 2012a; Harris and Macmillan-Lawler, this volume). Failures at canyon heads cause upward retrogression of the canyon (Pratson and Coakley, 1996). Such failures at canyon heads are especially dangerous if canyon heads are close to the coast as they may trigger local tsunamis. For instance a relatively small failure of a canyon head offshore the port of Gioia Tauro (Italy) triggered a 5 m wave causing relevant damage to port facilities in 1977 (Colantoni *et al.*, 1992; Zaniboni *et al.*, 2014; Chiocci, this volume).

Less is known between the interaction of large-scale landslides and canyons. In previous years, we investigated several major landslide complexes and canyons systems off NW-Africa (e.g., Krastel *et al.*, 2006, 2012; Antobreh and Krastel, 2006, 2007; Henrich *et al.*, 2008). The passive margin off NW-Africa is characterized by relatively high accumulation rates (locally exceeding 10 cm/ka, Martinez *et al.*, 1999) as a result of high primary productivity caused by oceanic upwelling while fluvial input is very low. Mass wasting off NW-Africa has intensely been studied in the past. The NW-African continental margin is characterized by very large but infrequent mass wasting events (Fig. 1; Weaver *et al.*, 2000; Wynn *et al.*, 2000; Krastel *et al.*, 2012). In addition, several major canyon systems were discovered along the margin despite the low fluvial input in current times (e.g., Antobreh and Krastel, 2006; Henrich *et al.*, 2010; Pierau *et al.*, 2011).

In this paper, we will focus on the interaction between major mass wasting events and canyon evolution based on selected examples. We will show that canyon dynamics may be heavily affected by large scale mass wasting in some cases while its influence is relatively minor for other systems.

Material and methods

Hydroacoustic, seismic and sediment core data have been recorded during numerous cruises in the past years. Sediment echo sounder data were mainly collected using an Atlas Parasound system, which is a 4 kHz narrow beam parametric system. Bathymetric data were acquired using different multibeam echo sounders. High-resolution multi-channel seismic data were collected using single GI-Guns (Volumes of 0.4 or 1.7 l) and different streamer systems with small group distances. Sediment samples were taken by means of standard gravity and giant box corers.

Results

Fig. 1 shows the distribution of canyon/channels and landslide deposits in the survey area. The survey area extends from the Senegal in the south (~12°N) to the southern part of Morocco in the north (~35°N). We point out that not the entire margin is mapped with hydroacoustic systems and that additional surveys will result in a more detailed map.

Canyons and channels are widespread along the entire margin. Some of them are relatively small upper slope canyons and gullies while some have very large dimensions and can be traced for more than 500 km from the shelf break to the continental rise. The largest systems are the Agadir canyon off Morocco and the Cap Timiris Canyon/Channel off Mauritania. Both are described in more detail below. Several large-scale landslides are found along the margin itself. The largest landslides (from south to north) are the Dakar Slide, the Mauritania Slide Complex, the Cap Blanc Slide, the Sahara Slide and the Agadir Slide. Each of them is affecting several 10,000 km^2 of sea floor. Large-scale landslides are also widespread on the flanks of the Canary Islands but they are beyond the scope of this paper.

Different types of interaction between large-scale mass wasting and submarine canyons were found for different sections of the margin. In the following we will focus here on i) the section off Senegal (Dakar Slide and Dakar Canyon), ii) the area off Mauritania (Cap Timiris Canyon and Cap Blanc and Mauritania Slides) and iii) the Agadir Canyon and landslide area.

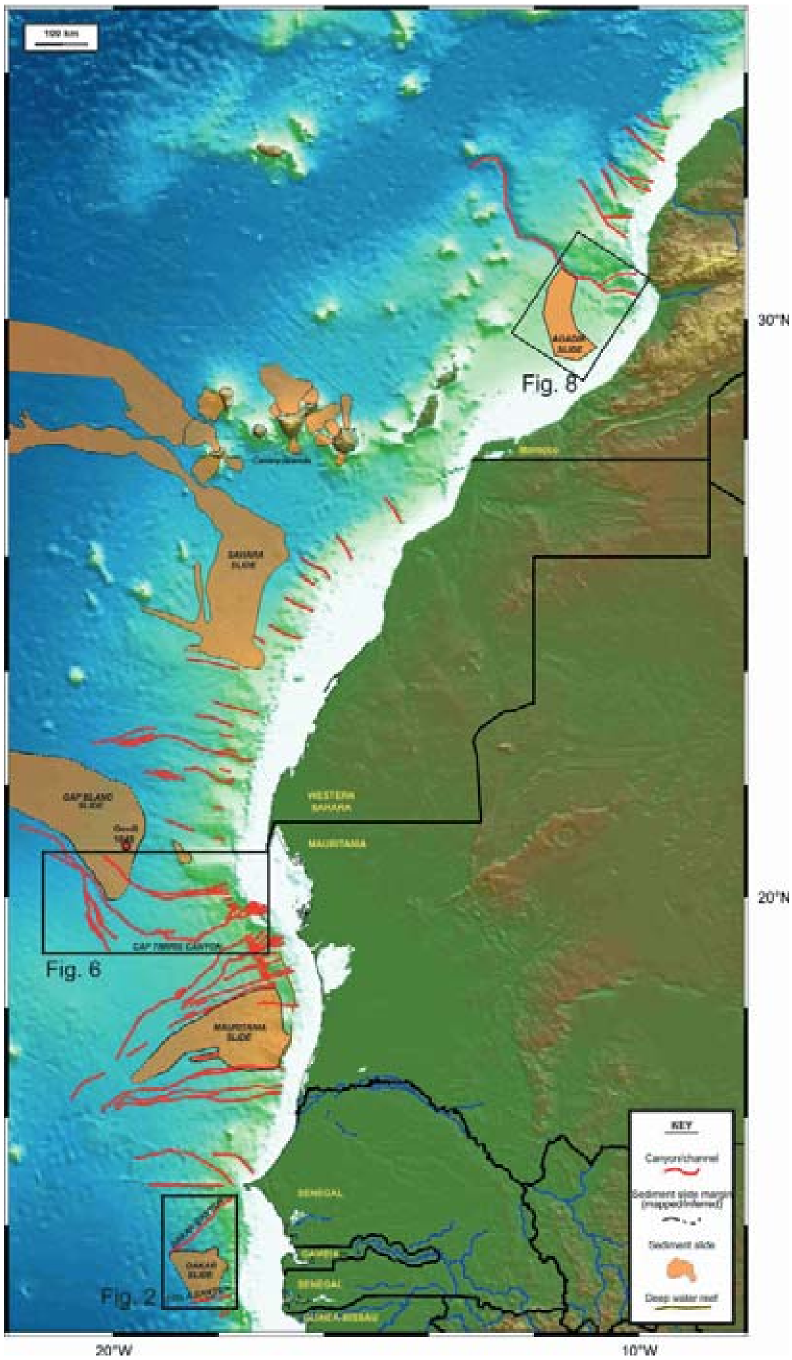


Figure 1. Distribution of canyon/channels and landslide deposits off NW-Africa.

Dakar Canyon and Dakar Slide off Senegal

The Dakar Canyon incises the continental slope of Senegal neat the city of Dakar (Fig. 1). The canyon was mapped from the upper slope at a water depth of ~1300 m down to a water depth of ~ 4100 m where the canyon disappeared (Fig. 2, Pierau *et al.*, 2010, 2011). At the upper slope, the canyon is deeply incised in the slope sediments (up to 700 m) and shows a width of ~ 10 km. Incision depth reduces to less than 20 m at the continental rise at 4100 m water depth where it finally disappears. The canyon is almost straight and does not show any significant sinuosity; it runs in a NW–SE direction. The Dakar Canyon is typically V-shaped in the proximal sector and changes into a more U-shape pattern at the distal part. Generally, the canyon bottom is filled with coarse material (Pierau *et al.*, 2011). Several cores taken in the canyon thalweg indicate that the highest frequency in turbidite activity in the Dakar Canyon is confined to major climatic terminations when remobilization of sediments from the shelf has been triggered by the eustatic sea-level rise. In addition, some episodic turbidite events coincide with the timing of Heinrich events in the North Atlantic. During these times, continental climate has changed rapidly, with evidence for higher dust supply over NW Africa, which has fed turbidity currents. (Pierau *et al.*, 2010).

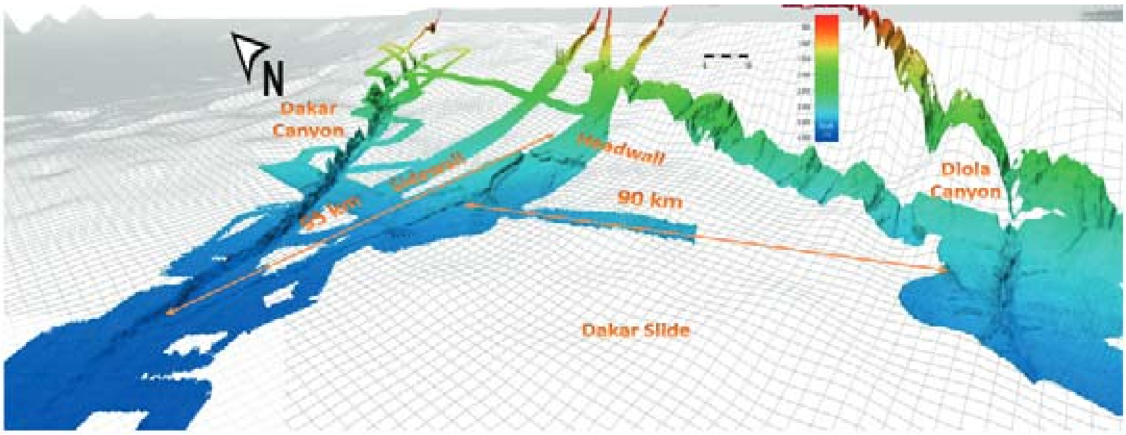


Figure 2. Perspective view of Dakar Canyon and Dakar Slide. Modified after Krastel *et al.* (2012).

Dakar Slide is only partly mapped (Fig. 2). It shows a headwall with a length of at least 90 km in water depths of 2,000–3,100 m. The slide is situated between two canyons, the Dakar Canyon in the north and the Diola Canyon in the south (Meyer *et al.*, 2012). The age of Dakar Slide is unknown. The bathymetric data show that the headwall of the Dakar Slide intersects with Dakar canyon at about 3900 m water depth (Fig. 2). A series of Parasound profiles (Fig. 3) illustrates the change of canyon morphology in this region. A first cross section in about 3300 m of water depth (Fig. 3a) shows a ~300-m deep incised V-shaped canyon. The cross section changes to a U-shape in ~ 3700 m water depth. Incision depth is ~ 150 m and levees start to develop (Fig 3b). Significant changes occur further downslope. The channel-depth decreases significantly to about 75m at the point, where the headwall of Dakar Slide hits the canyon. A partly destroyed levee is visible on the SE-side of the canyon (Fig. 3c), while the NW levee seems to be intact. No channel is visible only 5 km further downslope (Fig. 3d) but the sediment echo sounder data show a rough sea floor, which is typical for landslide deposits. Hence, we assume that the canyon was destroyed by the landslide.

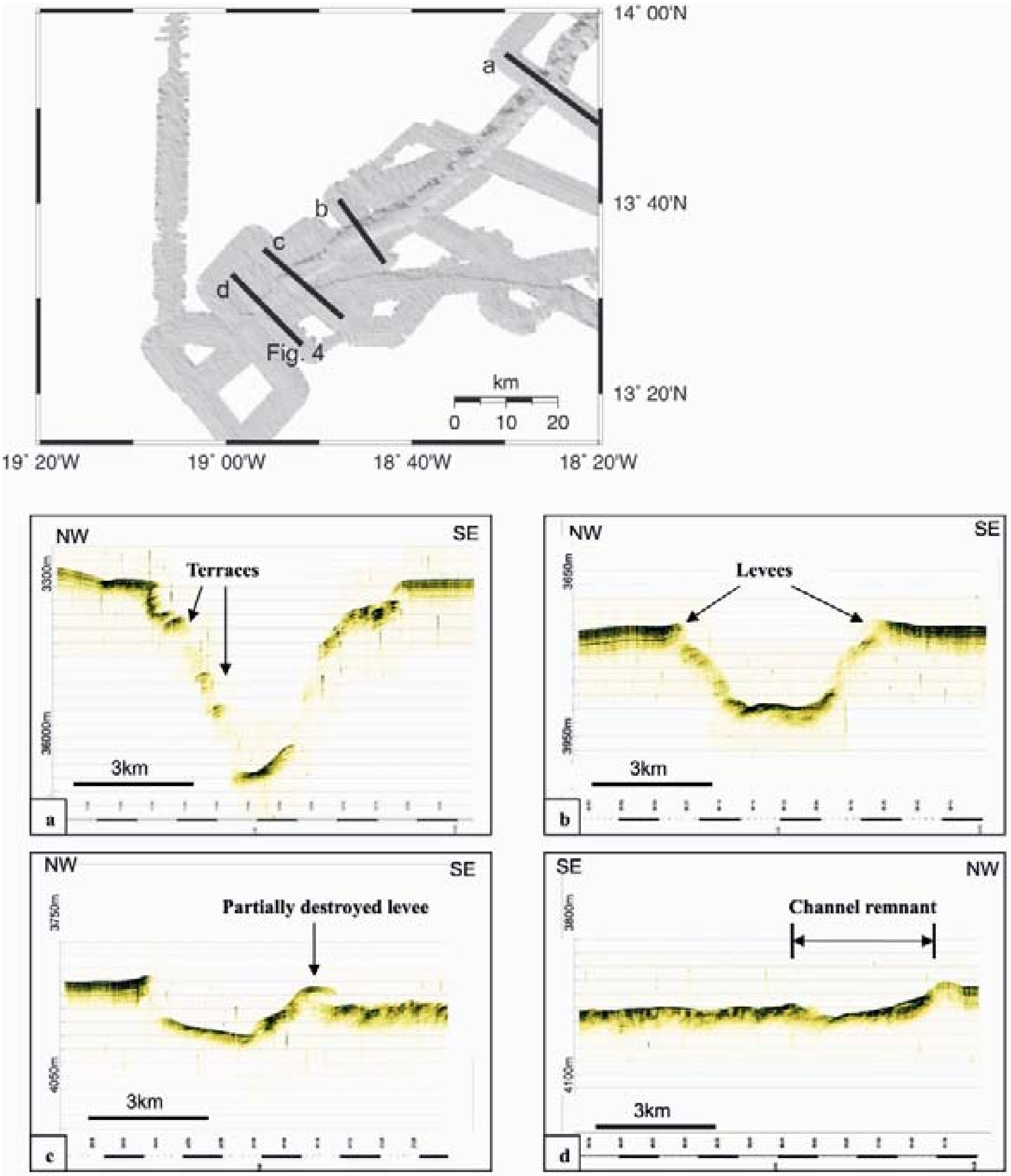


Figure 3. Close-up of the area where the headwall of Dakar Slide hits the Dakar Canyon. The decreasing incision depth and the partial destruction of the levee suggest that Dakar Slide destroyed the canyon. Note that the profile shown as figure d is plotted in reverse direction.

The internal structure of the channel is imaged on seismic data (Fig. 4). The profile can be subdivided horizontally into three parts. The canyon itself, which is destroyed, a northern part where sediments are continuous and undisturbed, and a southern part where the sediments are disturbed. The southern units represent landslide deposits, while the northern part shows a well-developed levee. The internal fill of the canyon clearly changes its seismic appearance. High-amplitude chaotic reflectors are found at the base of the canyon, which is overlain by a thick transparent unit. Some high-amplitude partly deformed reflectors are imaged close to the present-day sea floor.

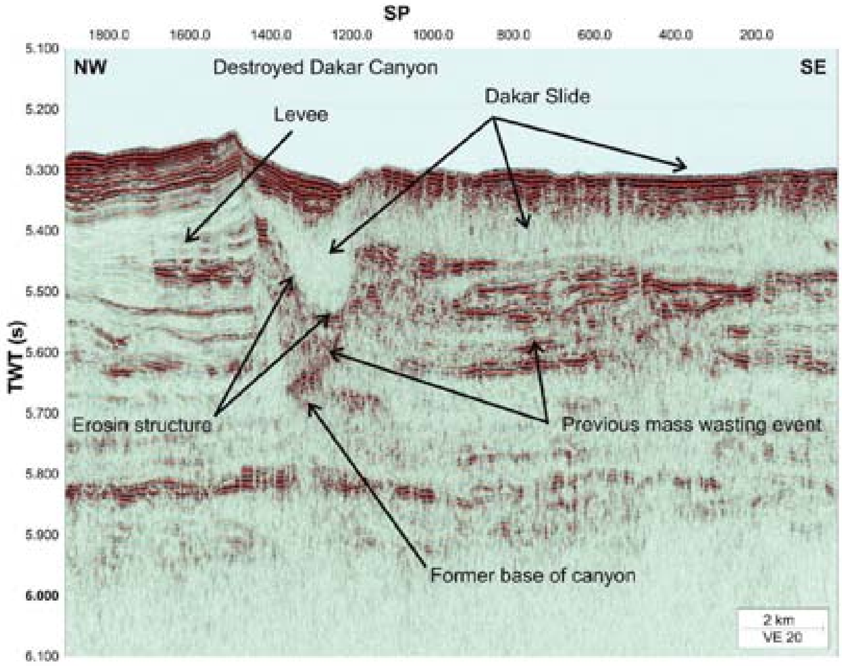


Figure 4. Seismic profile crossing destroyed Dakar Canyon. The formerly deeply incised canyon is now filled by mass wasting deposits. See Fig. 3 for location of profile. Modified after Meyer *et al.* (2012)

Although absolute times of the single processes cannot be established from seismic data alone, their chronology can be determined (Fig. 5). After the canyon was formed, it was a pathway for turbidity current, which deepened the canyon. A levee structure was initiated due to overspill of the turbidity currents. The right-hand northern levee is better developed than the left-hand southern levee. After the canyon was terminated the first time by a mass wasting event, the canyon became active again. It was eroded by turbidity currents, which contributed to the levee formation documented by undisturbed sediments. After the second and final termination caused by the Dakar Slide, it is most likely to assume that the confined flows travelling in Dakar Canyon further upslope now spread over a large area further down slope.

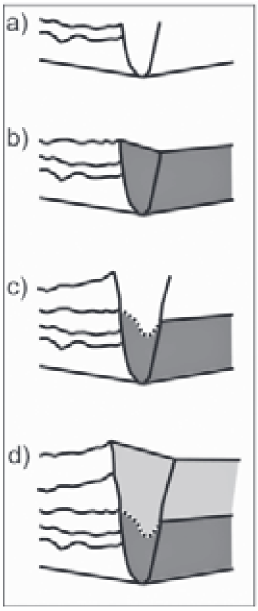


Figure 5. Sketch showing the evolution of lower Dakar Canyon. a) a deeply incised canyon is formed by turbidity currents. b) The canyon is destroyed by a landslide for the first time. c) The canyon was reactivated and eroded by turbidity currents. Levees are forming. d) The canyon was destroyed by Dakar Slide. Turbidity currents travelling in Dakar Canyon now spread over a large area further down slope.

The continental margin off Mauritania

The continental margin off Mauritania is described in detail by Krastel *et al.* (2006). Two large landslides (Mauritania Slide and Cap Blanc Slide) are found in this area. Turbidity current activity on the margin is evidenced by numerous gullies, canyons and channels. A large concentration of upper slope canyons and gullies is found in an area between Cap Timiris and the Mauritania Slide Complex, between 19°20'N and 18°20'N (Fig. 1). Typical incision depth is between 50 and 150 m deep at water depths of 1000-2000 m but may reach 250 m in some locations. The spacing is up to 10 canyons per 100 km at the 2000 m isobath. In between are numerous small gullies <25 m deep, which are roughly spaced 1-5 km apart at the 2000 m isobath. The canyons and gullies merge downslope and form shallow channels, which are usually <70 m deep at a water depth of 3000 m. The number of canyons and channels north and south of the described section is significantly less. Thus we identified a spacing of three canyons per 100 km between 21°N and 22°N at water depths of 1000-2000 m (Krastel *et al.*, 2006).

The largest and most fascinating canyon/channel is the Cap Timiris Canyon (Fig. 6). This feature is described in detail by Antobreh and Krastel (2006) and Zühlsdorff *et al.* (2007). The canyon can be traced for more than 500 km, though not all sections have been mapped in detail (Fig. 6). The upper ~220km (Fig. 6b) show a dominantly V-shaped and deeply entrenched canyon exhibiting many fluvial features including dendritic and meander patterns, cut-off loops and terraces. Terraces exhibit a variety of internal structures, suggesting they originated through different processes including sliding/slumping, uplift-induced incision and lateral accretion (Antobreh and Krastel, 2006). Cap Timiris Canyon is one of very few prominent examples of a huge submarine meandering channel system that does not have a recent obvious or even active connection to a sub-aerial river system in the hinterland (Zühlsdorff *et al.*, 2007).

However, canyon origin is ascribed to an ancient river system in the adjacent, presently arid Sahara Desert that breached the shelf during a Plio/Pleistocene sea level lowstand and delivered sediment directly into the slope area. Antobreh and Krastel (2006) suggest that the initial invading unchannelized sheet of sand-rich turbidity flows initiated canyon formation by gradually mobilizing along linear seafloor depressions and fault-controlled zones of weakness. They propose that the development of canyon morphology and structure was influenced by the stages of active flow of the coupling river system, and hence could act as a proxy for understanding the paleo-climatic evolution of a 'green' Sahara since Plio/Pleistocene times.

The more distal part of Cap Timiris Canyon, about 500 km off the shelf break (Fig. 6c), is made out of a number of NW-SE oriented linear segments, up to 20 km or more in length. It also displays at least four older abandoned linear channel segments, which are either partly or completely infilled. The channel depth seems to decrease quickly in the distal segment shown on Fig. 6c. This brings up the question of whether the channel was destroyed by the nearby Cap Blanc Slide in a way similar as the Dakar Canyon. Sediment echo sounder data, however, show that the deposits of the Cap Blanc Slide onlap the well-developed levee of the distal Cap Timiris Canyon but did not destroy the levee or the channel (Fig. 7). Hence, the decreasing channel depth is most likely caused by the decreasing slope gradient and reduced transportation energy of the turbidity currents.

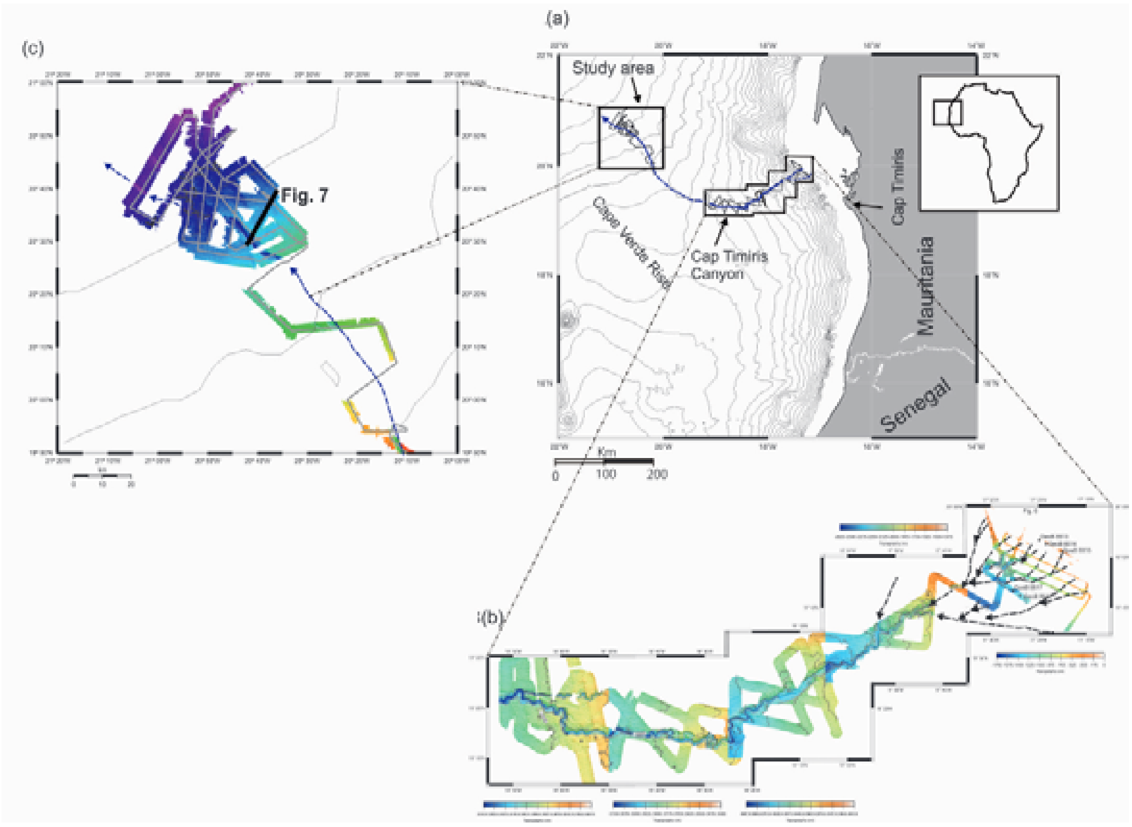


Figure 6. Bathymetric map of Cap Timiris Canyon off Mauritania.

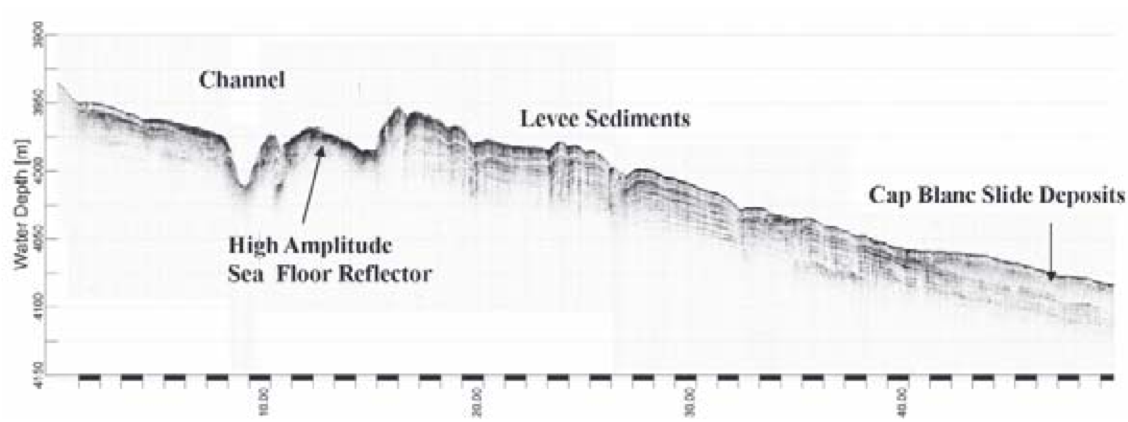


Figure 7. Sediment echo sounder profile showing an onlap of the deposits of the Cap Blanc Slide on the levee of distal Cap Timiris Canyon. See Fig. 6 for location of profile. Modified after Krastel *et al.* (2006).

It is interesting to note that most canyons/channels off Mauritania are found in areas that are not affected by large scale mass wasting (Fig. 1). Thus canyons are found immediately north and south of the Mauritania Slide Complex but no prominent canyons are found upslope of the slide headwall or buried beneath the slide sediments. Hence, it is unlikely that canyons are just not visible in the landslide areas because they are destroyed by the landslides. Krastel *et al.* (2012) suggest that canyons off Mauritania represent an effective pathway for regular downslope sediment transport by turbidity currents, evacuating sediments away from the slope, while the areas without canyons become increasingly burdened by deposition of thick sedimentary successions. Infrequent triggers, especially the lack of regular earthquakes, result in long periods of undisturbed sediment accumulation; these thick sedimentary packages occasionally fail as large landslides in areas without canyons.

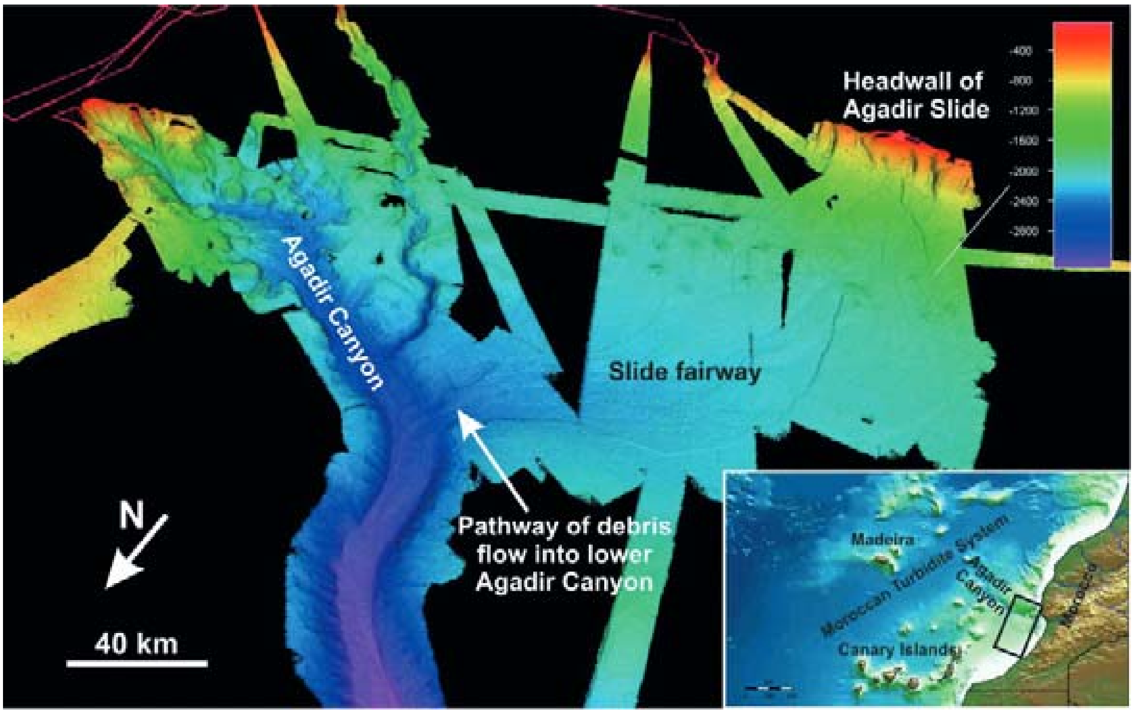


Figure 8. Perspective view of Agadir canyon and Agadir Slide. See Fig. 1 for location (taken from Krastel *et al.*, 2016).

Agadir Canyon and Agadir Slide

Agadir Canyon is one of the largest submarine canyons in the world; it is 450 km long, up to 30 km wide and 1250 m deep. It incises the Morocco Shelf at 200 m water depth and terminates on the floor of Agadir Basin at 4300 m water depth (Figs. 1, 8). The upper canyon has two shelf-incising tributaries that merge at a depth of 2200 m (Fig. 9); below this the canyon forms a single conduit that curves around a series of volcanic seamounts on the lower slope (Wynn *et al.*, 2000). The Agadir Canyon supplies sediment to the Moroccan Turbidite System, which comprises three interconnected deep-water basins: Agadir Basin, Seine Abyssal Plain and Madeira Abyssal Plain (Wynn *et al.*, 2002). Coring and drilling of the Moroccan Turbidite System revealed a long sequence of turbidites, mostly sourced from the Moroccan continental margin and the volcanic Canary Islands. Individual flow deposits can be correlated between all three basins, across a distance >1200 km (Wynn *et al.*, 2002; Frenz *et al.*, 2009). Individual flow deposits in the Moroccan Turbidite System may reach volumes of >100 km^3, although these large-scale events are relatively infrequent with a recurrence interval of about 10,000 years (over the last 200,000 years).

While the Moroccan Turbidite System is extremely well investigated, almost no data of the potential source areas of the major turbidites originating in the Agadir canyon area were available until recent times. This area was surveyed during RV Merian cruise MSM32 in late 2013. The Agadir Slide originating about 200 km south of the canyon was considered as potential source for some of the major turbidites discovered in the Moroccan Turbidite System as major landslides may disintegrate and transform into turbidity currents. The flow dynamics of this major landslide was investigated by Krastel *et al.* (2016). They showed that the Agadir slide originated as slab-type failure and rapidly disintegrated and transformed into a debris flow, which entered Agadir Canyon at 2500 m water depth (Figs 8; 9). However, the debris flow did not disintegrate into a turbidity current when it entered the canyon despite a significant increase in slope angle. The material was transported as debrite for at least another 200 km down the canyon but not reach the wider Moroccan Turbidite System.

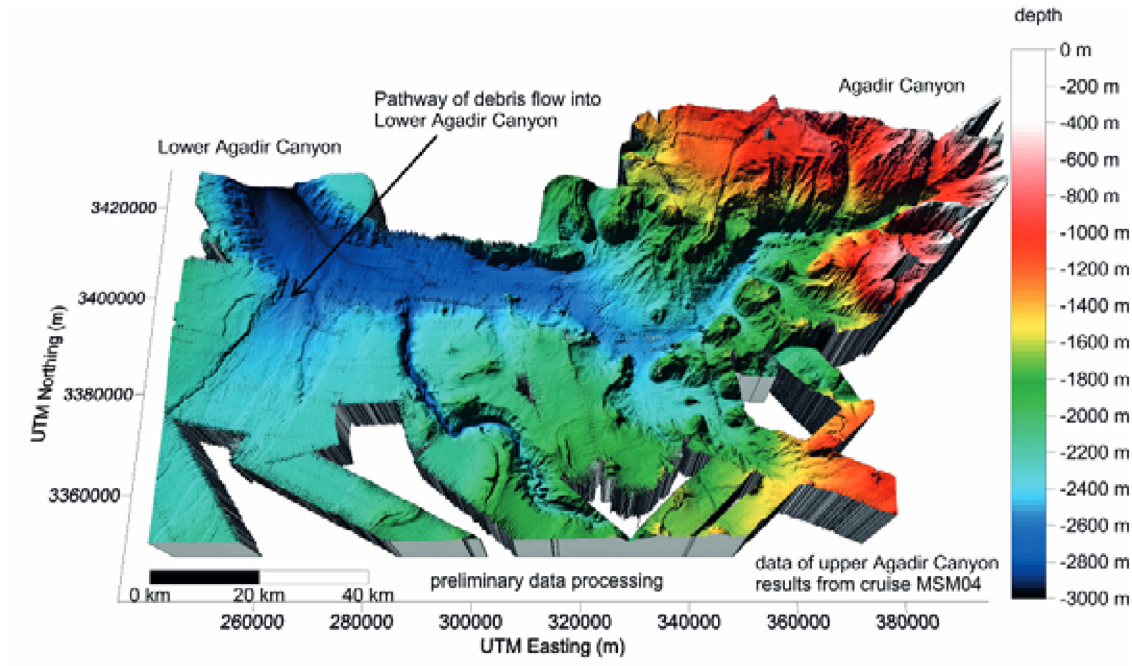


Figure 9. Perspective view of the upper section of the Agadir canyon showing two main tributaries but no clear indications for large-scale failures. Modified after Krastel *et al.* (2016).

We therefore assume that the major turbidites deposited in the Moroccan Turbidite System must have originated from the headwall area of Agadir Canyon. The bathymetric map, however, does not show any obvious indications for major slope failures in this region. This observation suggests that the turbidity currents originate in the head region of Agadir Canyon without leaving major landslide scarps behind. The initial failure was most likely small but the turbidity currents eroded significant amounts of sediments from the canyon floor during the downslope journey, which were incorporated in the turbidity currents. Deposition took place when the turbidity currents reached the Moroccan Turbidite System where they spread over a large area at very low slope angles.

Discussion and conclusion

Submarine mass wasting is an important process during canyon evolution. Failures at canyon heads and canyon flanks are important processes for canyon initiation, upward retrogression of the canyon head, and widening of the canyon. Such failures are usually relatively small but may be widespread in canyons systems. In this manuscript, we show that giant landslides originating at the open slope at the NW-African continental margin may also influence canyon evolution. This is clearly demonstrated by the Dakar Slide and Dakar Canyon of Senegal. The Dakar Canyon is a deeply incised, almost straight canyon, which is destroyed repeatedly by the large Dakar Slide. Dakar Slide enters Dakar Canyon in about 3900 m water depth, where Dakar Canyon is currently about 75 m deep and only 'protected' by a small left-hand levee. This levee is partly destroyed by the Dakar Slide, which filled the canyon completely. Turbidity currents originating at the upper, still intact part of Dakar Canyon spread over larger areas after the canyon was destroyed, as they are no longer confined by the canyon. Hence, the destruction of the canyon leads to a reorganization of sediment transport pathways. Such a type of destruction is only possible if levee heights are not too high. A similar type of construction and reorganization of canyons systems is also observed for certain 'sedimentary' canyons in the Mediterranean Sea, e.g. in the Rosetta canyon area of the Nile river (Mascle *et al.*, this volume).

A major landslide (Cap Banc Slide) is also found in close vicinity to the distal part of Cap Timiris Canyon off Mauritania. The landslide, however, is not entering the canyon because it is not able to pass the well-developed right-hand levee of the canyon. Another type of interaction between large canyons and landslides is found at Agadir Canyon. A major landslide enters the canyon in about 2800 m water depth where the canyon is still almost 500 m. The landslide is therefore not able to destroy the canyon but thick debrite deposits are found at the canyon floor. We suggest that canyons with moderate incision depth and without well-developed levees are especially prone to destruction by landslides.

The widespread presence of canyons may prevent the slope to fail because canyons represent an efficient pathway for semi-continuous downslope sediment transport of major amounts of sediments. This setting is not leading to the accumulation of thick sedimentary successions, which may fail as large-scale landslides.

While our findings are based on a small number of examples at the NW-African continental margin, we expect similar settings at other passive continental margins. But we do not think that our findings are relevant for active margins characterized by more frequent but generally smaller landslides. Such landslides are too small for having a significant influence on the canyon morphology and resulting sediment transport pattern.

---

* this chapter is to be cited as:

Krastel S. 2015. Interaction of large landslides and canyons off NW-Africa. pp. 59 - 69 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.

Changes in sediment accumulation rates within NW Mediterranean submarine canyons caused by bottom trawling activities

Pere Puig[1], Pere Masqué[2,3,4], Jacobo Martín[1,5], Sarah Paradis[2], Xènia Juan-Díaz[2], Miguel Toro[2] and Albert Palanques[1]

[1] *Institut de Ciències del Mar (ICM-CSIC), Barcelona, Spain*
[2] *Universitat Autònoma de Barcelona, Bellaterra, Spain*
[3] *Oceans Institute and School of Physics, The University of Western Australia, Crawley, Australia*
[4] *School of Natural Sciences, Edith Cowan University, Joondalup, Australia*
[5] *Centro Austral de Investigaciones Científicas (CADIC-CONICET), Ushuaia, Argentina*

Abstract

The disturbance of the marine sedimentary environments by commercial bottom trawling is a matter of concern. The direct physical effects of this fishing technique include scraping and ploughing of the seabed and increases of the near-bottom water turbidity by sediment resuspension. However, the quantification of the sediment that has been resuspended by this anthropogenic activity over the years and has been ultimately transferred along and across the margin remains largely unaddressed. The analysis of sediment accumulation rates from sediment cores collected along the axes of several submarine canyons in the Catalan margin (northwestern Mediterranean) has allowed to estimate the contribution of bottom trawling to the present-day sediment dynamics. ^{210}Pb chronologies, occasionally supported by ^{137}Cs dating, indicate a rapid increase of sediment accumulation rates since the 1960-70s, along with a strong impulse in the industrialization of the trawling fleets of this region. Such increase has been associated to the enhanced delivery of sediment resuspended by trawlers from shelf and upper slope trawling grounds towards submarine canyons, as a consequence of the rapid technical development at that time, in terms of engine power and gear size. This change has been observed in La Fonera (or Palamós) Canyon (one of the most prominent canyons of the region) at depths greater than 1700 m, while in other canyons not so deeply incised it is restricted to shallower regions (~1000 m in depth) closer to fishing grounds. Two sampling sites from La Fonera and Foix submarine canyons that exhibited high sediment accumulation rates (0.6-0.7 cm y^{-1}) were revisited several years after the first chronological analyses. These two new cores revealed a second and even more significant increase of sediment accumulation rates in both canyons which occurred circa 2000 and reached values higher than 2 cm y^{-1}. This second change at the beginning of the 21st century has been attributed to a preferential displacement of the trawling fleet towards slope fishing grounds surrounding submarine canyons, and to new technical improvements in trawling vessels, presumably related to subsidies and aids provided by the European Commission to the fishing industry.

Introduction

Bottom trawlers are commercial fishing vessels actively pulling nets along the seafloor with the aim of capturing fish and other marine species for human consumption or other industrial uses. Bottom trawling is carried out worldwide and its depth range has progressively expanded during the last years, from shelf and coastal environments towards deep-sea regions (Morato *et al*., 2006). The Catalan continental margin (NW Mediterranean) has supported an important bottom trawling activity during decades, currently reaching down to 800-900 m water depth. Deep-sea trawling in this region is mainly targeting the highly priced blue and red shrimp *Aristeus antennatus* (Risso, 1816), whose life cycle is closely related to submarine canyons environments (Sardà *et al*., 1994).

Bottom trawling poses many biological and physical impacts in the marine environment, and has been identified as a major force of seafloor disturbance by remobilizing and resuspending sediments, inducing the formation of nepheloid layers and sediment-laden flows, and by causing major changes in the morphology of continental slopes (Puig *et al*., 2012; Martín *et al*., 2014c). The trawling-induced resuspended sediment particles can be intercepted by submarine canyons and transported down-canyon, thus increasing sediment fluxes in deeper canyon regions.

An early study conducted in La Fonera (or Palamós) Canyon that analyzed a sediment core collected in the lower canyon axis, at 1750 m depth, documented a doubling of the sedimentation rate after the 1970s. Parallel analysis of historical fisheries data revealed that the local trawling fleet rapidly increased in terms of engine power during the same time period, which led to propose that the new sediment accumulation trend was a consequence of the enhancement of trawling-induced sediment resuspension and transport towards the lower canyon reaches (Martín *et al*., 2008).

To validate the hypothesis of a sedimentary regime shift caused by trawling activities in the Catalan margin, and to provide a broader view of this phenomenon at a margin-scale, several sediment cores taken from submarine canyons have been recently analyzed, including new cores from previously studied sites in La Fonera Canyon (Martín *et al*., 2008), and in Foix Canyon (Sánchez-Cabeza *et al*., 1999). Here we report the main results derived from this new coring effort and discuss the observed changes in sediment accumulation rates.

Methods

A KC Denmark A/S 6-tube (inner diameter 9.4 cm; length 60 cm) multicorer was used to collect undisturbed surface sediment cores along the axis of several submarine canyons incised in the Catalan margin (Fig. 1A). These cores were obtained during the past four years in several oceanographic cruises onboard the RV *García del Cid*.

In May 2011, a sediment core was collected in La Fonera (Palamós) Canyon (PC) at 1820 m water depth, 1.5 km away from the core analyzed in the same canyon region by Martín *et al*. (2008). In July 2012, three sediment cores were collected in Arenys Canyon (AC) at 1074 m, 1410 m and 1632 m water depth, respectively. During the same cruise, two other sediment cores were obtained in Besòs Canyon (BC) at 1238 m and 1487 m water depth. This submarine canyon was revisited in September 2014 to collect a shallower core at 810 m water depth. In October 2013, a sediment core was obtained at 865 m water depth in Foix Canyon (FC), close to the location where a former core was collected in 1993 and studied by Sánchez-Cabeza *et al*. (1999).

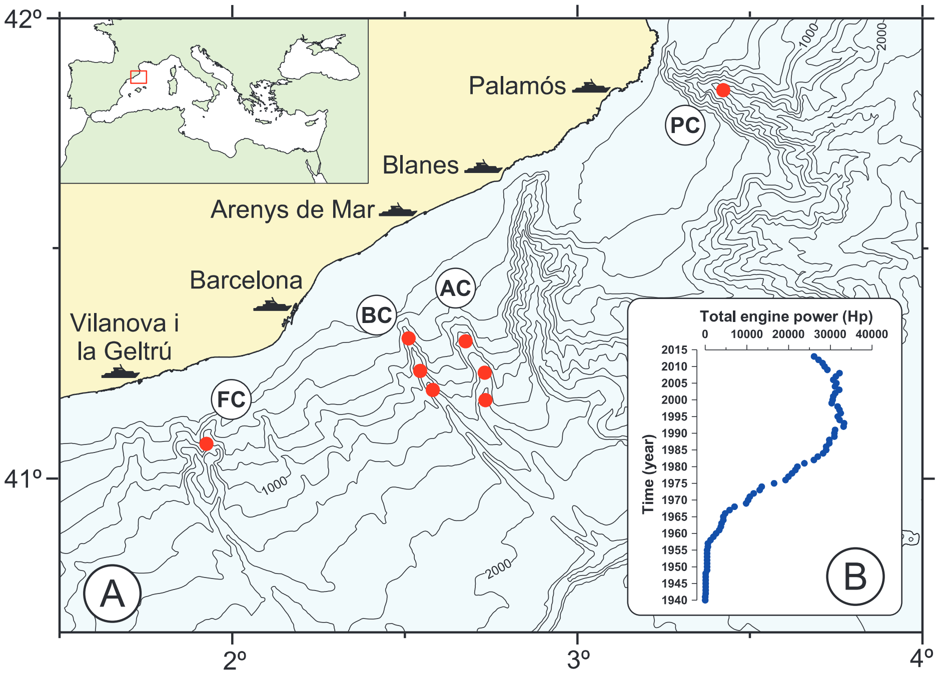


Figure 1. **A**: Bathymetric map of the Catalan margin showing the submarine drainage network and the major fishing harbors of this region (black ships). Sediment coring (red dots) was conducted at the axes of La Fonera, also known as Palamós Canyon (PC), Arenys Canyon (AC), Besòs Canyon (BC) and Foix Canyon (FC). Bottom trawling activities on this margin are conducted on a daily basis (excluding weekends and local holidays) on the shelf and upper continental slope, including submarine canyon rims and axes, down to 800-900 m water depth. **B**: Plot showing the evolution over time of the official total engine power (sum of the horsepower of all trawlers) of the major fishing harbors shown in the map. Note the rapid increase that occurred during the 1960-70s.

Sediment cores were sliced on-board at 1 cm intervals and the sections obtained were freeze-dried for further analysis. For the purpose of this document, only ^{210}Pb and ^{137}Cs activities are presented, from which sediment accumulation rates over the last 100-150 years have been derived. The concentrations of ^{210}Pb were determined by alpha-spectroscopy following Sánchez-Cabeza *et al*. (1998). ^{137}Cs concentrations were measured by γ-counting of dried, homogenized samples in calibrated geometries for $2\text{-}3\cdot10^5$ s on a high purity intrinsic germanium detector. Sediment accumulation rates were calculated based on a one-dimensional, steady-state constant ^{210}Pb flux/constant sedimentation model constrained by the ^{137}Cs concentration profiles (Masqué *et al*., 2003).

Historical data of the characteristics of the trawling fleet operating in the region studied were obtained from official bulletins and databases provided by the Spanish Ministry of Agriculture, Livestock and Environment. The temporal evolution of the total engine power (sum of the horsepower of all trawlers) of the major harbors of this area (black ships in Fig. 1A) is shown in Fig. 1B. Total engine power is considered to be a reliable proxy for the size and weight of the gear that a boat can tow, as well as for working depth and haul duration, indicative of the capacity to resuspend bottom sediments (Martín *et al*. 2014c).

Results and Discussion

Arenys Canyon

The sediment cores collected in Arenys Canyon were previously studied by Toro (2013) and are presented in Fig. 2. The results show a constant and fairly similar sediment accumulation rate at the two deeper stations, accounting for 0.057 ±- 0.001 g $cm^{-2}\cdot y^{-1}$ (0.082 ± 0.002 cm y^{-1}) at 1410 m water depth and 0.066 ± 0.001 g $cm^{-2}\cdot y^{-1}$ (0.096 ± 0.002 cm y^{-1}) at 1632 m water depth. However, two clear sediment accumulation rates were observed at the shallower site: the lower part of the sediment core (13-20 cm) displays an accumulation rate of 0.054 ± 0.002 g cm^{-2}·y^{-1} (0.063 ± 0.003 cm y^{-1}), while the surface sediment unit (0-14 cm) has a higher accumulation rate of 0.203 ± 0.009 g cm^{-2}·y^{-1} (0.332 ± 0.015 cm y^{-1}). The sedimentation model estimates that the change in the accumulation rates took place during the 1960-70s.

In this submarine canyon, the change in sediment accumulation rates attributable to the resuspension by trawling activities is only recorded in the shallower core closer to fishing grounds, where sedimentation rates have increased five times with regard to the natural (pre-1960-70s) ones. The constant and similar sedimentation rates observed in the two deeper cores located offshore from the trawled slope regions suggest that the trawling-resuspended sediment in this canyon region is mainly transported along-margin, with limited off-shore dispersal. The morphological characteristics of the Arenys Canyon, with a wide canyon axis and absence of a defined canyon head incised on the shelf edge, may favor this behavior.

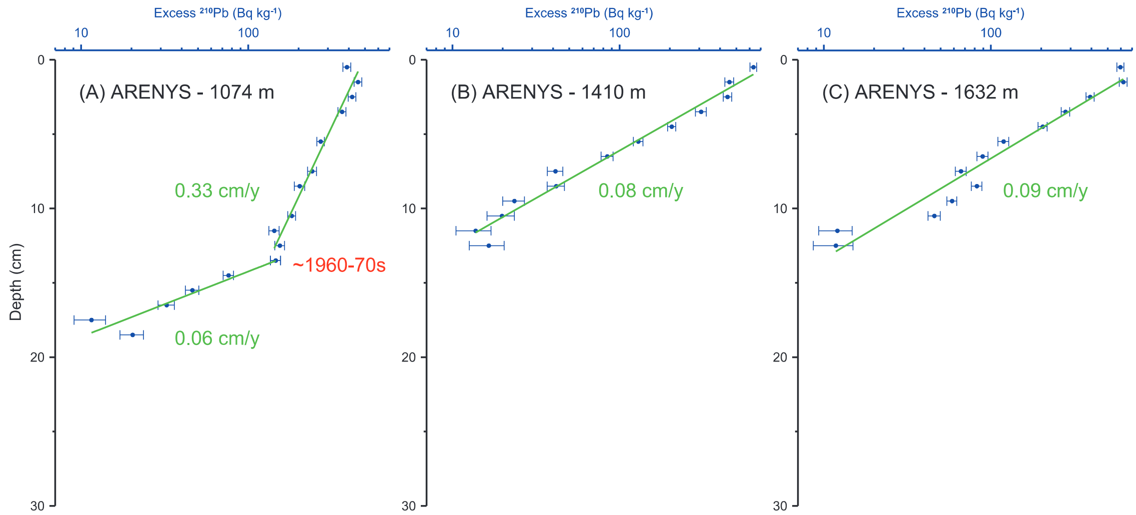


Figure 2. Excess ^{210}Pb activity profiles and sedimentation rates of the three sediment cores collected along the Arenys canyon axis in July 2012. See core locations in Figure 1A.

Besòs Canyon

The two deeper cores collected in July 2012 in the Besòs canyon axis were previously studied by Juan-Díaz and Paradis (2014) and are presented here together with a shallower core collected in September 2014. At the deeper site, 1487 m water depth (Fig. 3 C), the sediment core displays an apparent surface mixed layer (SML) and a constant sediment accumulation rate down to 18 cm of 0.065 ± 0.002 g cm^{-2}·y^{-1} (0.091 ± 0.002 cm y^{-1}). This sedimentation rate is in agreement with those found in the two deeper cores from the neighboring Arenys Canyon (Figs. 1A and 2). The excess ^{210}Pb concentration profile from the sediment core collected at 1238 m water depth (Fig. 3 B) is more complex. At the lower part of the core (20-26 cm), a constant accumulation rate of 0.083 ± 0.006 g cm^{-2}·y^{-1} (0.117 ± 0.009 cm y^{-1}) is observed. Above, a portion of the sediment core (15-19 cm) shows an anomalous excess ^{210}Pb activity profile denoting a non-steady-state sedimentation, and above it (5-14 cm) the previous sediment accumulation rate is reestablished, accounting for 0.081 ± 0.005 g cm^{-2}·y^{-1} (0.125 ± 0.008 cm y^{-1}). Finally, in the uppermost part of the sediment core, an apparent SML of 4 cm is observed. In general, a mean sedimentation rate of ~0.12 cm y^{-1} seems to prevail through time at this canyon site, although it was disrupted during a certain period by the arrival of sediments at a non-constant rate. The X-radiograph and grain-size analysis of this sediment core (not shown) do not suggest that this portion of the sedimentary column could be caused by a massive arrival of sediments in a single event (i.e., as a turbidite or debris flow). A possible explanation could be a transitory alteration of the natural fluxes by the onset of trawling activities in this submarine canyon, which affected this part of the canyon for a limited period of time, since the sedimentation model suggests that this disruption occurred circa the 1960-70s.

At the shallower canyon location, at 810 m water depth, one observes a clear change in sediment accumulation rates (Fig. 3A). The excess ^{210}Pb activity profile from this sediment core shows that the bottom part (30-50 cm) displays a constant accumulation rate of 0.34 ± 0.03 g $cm^{-2} \cdot y^{-1}$ (0.43 ± 0.03 cm y^{-1}) and that above this unit a non-steady-state sediment flux prevailed until present times. The sedimentation model indicates that this change occurred during the 1960-70s, in accordance with an alteration by bottom trawling activities of the natural sedimentation in the upper canyon reaches. Given the non-constant sediment flux in this upper portion of the sediment core, the accumulation rates could not be properly calculated, but if we integrate all the episodes that have constituted this sedimentary unit, taking into account the mass accumulated over the last 40-50 years, we obtain a mean sedimentation rate of 0.60-0.75 cm y^{-1}.

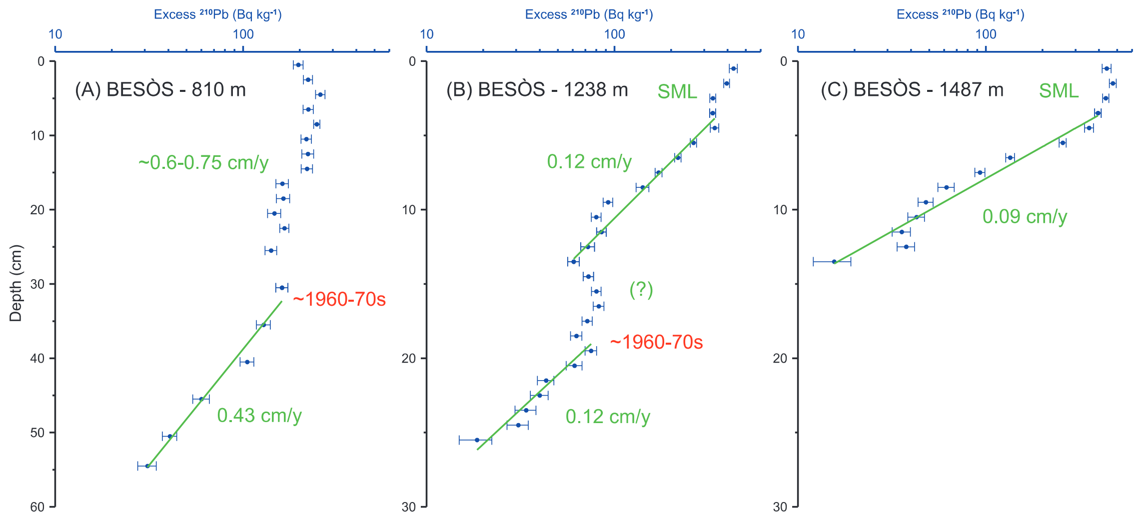


Figure 3. Excess ^{210}Pb activity profiles and sedimentation rates of the three sediment cores collected along the Besòs canyon axis in September 2014 (A) and in July 2012 (B and C). See core locations in Figure 1A.

La Fonera (Palamós) Canyon

The sediment core collected in 2002 in La Fonera canyon axis, at 1750 m water depth, recorded for the first time the post-1970s increase in the sedimentation rates linked to trawling activities (Martín *et al*., 2008). This core showed two contrasting sedimentary units: a deep unit without physical structures and a ^{210}Pb and ^{137}Cs derived sedimentation rate of 0.35 cm y^{-1} underlying a topmost sedimentary unit with a higher sedimentation rate, estimated at ~0.7 cm y^{-1}, as well as a well-preserved horizontal laminae. This increase in the accumulation rates and the preservation of physical structures in the sedimentary column was associated with the enhancement of trawling-induced sediment resuspension and transport towards deeper canyon reaches, observed to occur as sediment gravity flows funneled through tributary valleys on the canyon flanks (Palanques *et al*., 2006a; Martín *et al*., 2007). The excess ^{210}Pb and total ^{137}Cs activity profiles of this sediment core are shown in Fig. 4A.

In May 2011 a new sediment core was collected from a nearby canyon axis location at 1820 m water depth. The deepest layer at which ^{137}Cs was detected was at 44 cm, providing the ~1954 time marker, when this artificial radionuclide was first introduced to the environment as a consequence of atmospheric nuclear bomb testing. A broad increase of ^{137}Cs activity could be observed upwards, with two relative maxima at 39 and 36 cm depth, corresponding to the historical peak fallout around 1963 (Fig. 4B). From bottom to top, one can identify a section (47-37 cm) with a constant slope of the excess ^{210}Pb activity profile, denoting a steady-state accumulation of sediment that allowes calculating a rate of 0.20 ± 0.02 g cm^{-2} y^{-1} (0.25 ± 0.02 cm y^{-1}). From 36 cm depth to the sediment surface, the excess ^{210}Pb activity profile suggests a non-steady-state accumulation of sediment, presumably generated by a series of depositional events. The combination of the ^{210}Pb sedimentation model and the ^{137}Cs profile allows dates this change in the early 1970s. Taking into account the sediment thickness accumulated since that period, we obtain a mean sedimentation rate in the upper part of the core of ~1 cm y^{-1} (Fig. 4B).

To conduct a comparison between both cores, we considered that the regions of the two sediment cores where the slope of the excess ^{210}Pb vertical profile changes (i.e. due to a change in the sedimentation rates in the early 1970s), represent synchronous time horizons. Hence, in Fig. 4C the vertical axis of the core collected in 2002 was shifted 23 cm downwards to confront the sharpest ^{210}Pb discontinuities in both profiles. The synchrony of the change in sedimentation rates is further supported by the occurrence, at consistent depth intervals, of the ^{137}Cs maxima and the deepest appearance of detectable ^{137}Cs in the profile. Also, ^{210}Pb concentrations at the depths confronted in Fig. 4C are consistent with the radioactive decay of this radionuclide ($T_{1/2}$= 22.3 y) and with the nine years elapsed between coring operations.

Even though the pre-1970s sedimentation rate in the 2011 core has been estimated in 0.25 cm y^{-1} and the post-1970s layer accounts for an average rate of ~1 cm y^{-1}, the simple comparison with the 2002 core suggests that an enhancement of sediment accumulation might have occurred in this submarine canyon during the last decade. The 23 cm of sediment that appear to have been accumulated in nine years would represent a recent sedimentation rate of ~2.5 cm y^{-1}, an order of magnitude higher than the pre-1970s values (Fig. 4C).

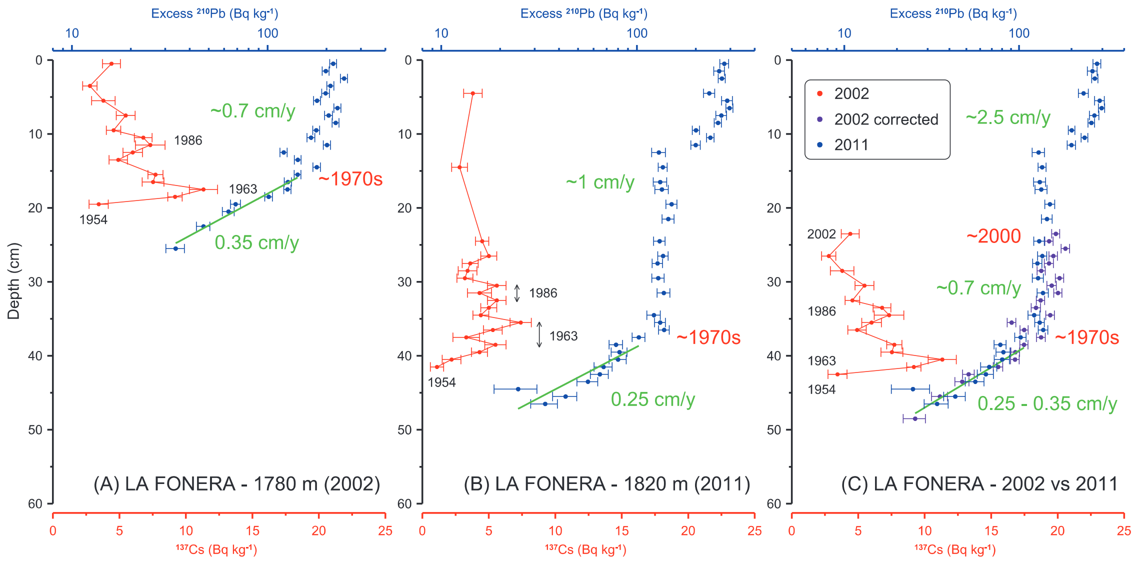


Figure 4. Excess ^{210}Pb and total ^{137}Cs activity profiles of sediment cores collected from the lower La Fonera (Palamós) canyon axis in 2002 and 2011. A doubling of the sediment accumulation rates after the 1970s was observed in 2002 by Martín *et al.* (2008). The core collected in 2011 confirms such a change, but the comparison between both cores suggests a more rapid change in sediment accumulation rates during the last decade.

Foix Canyon

In October 2013, a sediment core was obtained in the Foix canyon axis at 865 m water depth, revisiting the location of a previous core collected in April 1993 and analyzed by Sánchez-Cabeza *et al.* (1999). This allowed the study of the evolution of the sediment accumulation rates at this site with a time difference of 20 years (Fig. 5).

The 1993 sediment core showed a clear ^{137}Cs concentration profile, with the 1954 time marker occurring at 25 cm, the 1963 fallout peak at 23 cm, and the 1986 Chernobyl accident peak at 7 cm (Fig. 5A). The excess ^{210}Pb activity profile showed an apparent SML of 5 cm and a fairly constant slope that corresponded to a sediment accumulation rate of 0.51 ± 0.02 g cm^{-2} y^{-1} (0.58 ± 0.3 cm y^{-1}) (Sánchez-Cabeza *et al.*, 1999).

In the 2013 sediment core, analyzed by Juan-Díaz and Paradis (2014), ^{137}Cs was not measured and the horizon of supported ^{210}Pb was not reached (Fig. 5B). However, the same supported ^{210}Pb activity of the 1993 sediment core (30 ± 1 Bq·kg^{-1}) was assumed to reflect the excess ^{210}Pb activities. At the bottom of the 2013 sediment core anomalous values of excess ^{210}Pb activity were found and above them (43-23 cm) a constant ^{210}Pb slope allowed determining a unit with a sediment accumulation rate of 0.61 ± 0.04 g cm^{-2} y^{-1} (0.72 ± 0.04 cm y^{-1}). Above it, and up to the sediment surface, the ^{210}Pb slope increases considerably and accounted for a sediment accumulation rate of 1.6 ± 0.2 g cm^{-2} y^{-1} (2.2 ± 0.3 cm y^{-1}). The sedimentation model establishes this three-fold increase of sedimentation rates around year 2000 (Fig. 5B). This new change at the beginning of the 21st century is in agreement with the recent increase inferred in La Fonera Canyon after the comparison of the two available sediment cores (Fig. 4C).

The comparison between the two sediment cores collected 20 years apart in the Foix Canyon is shown in Fig. 5C. In this occasion, the excess ^{210}Pb activities from 1993 were corrected by theoretical decay until 2013, and both vertical profiles were overlapped by shifting the 1993 core 30 cm downwards. By doing so, the anomalous ^{210}Pb values at the bottom of the 2013 core coincided with similar anomalous values observed in the 1993 core around year 1963, at the level of the ^{137}Cs fallout peak. In fact, if the SML at the top of the 1993 core is not considered, two distinct ^{210}Pb slopes can be defined, being separated by these anomalous values. A top unit shows a sedimentation rate of 0.76 cm y^{-1} (considering that 23 cm were deposited in 30 years, from 1963 to 1993), which agrees with the 0.72 cm y^{-1} rate determined in the bottom part of the 2013 core; overlying a deeper unit with a lower sedimentation rate of 0.58 cm y^{-1} (Fig. 5C). Therefore, it seems that a subtle increase of sediment accumulation rates caused by bottom trawling activities may have also occurred in Foix Canyon during the 1960-70s, in accordance with the changes observed in other submarine canyons of the Catalan margin.

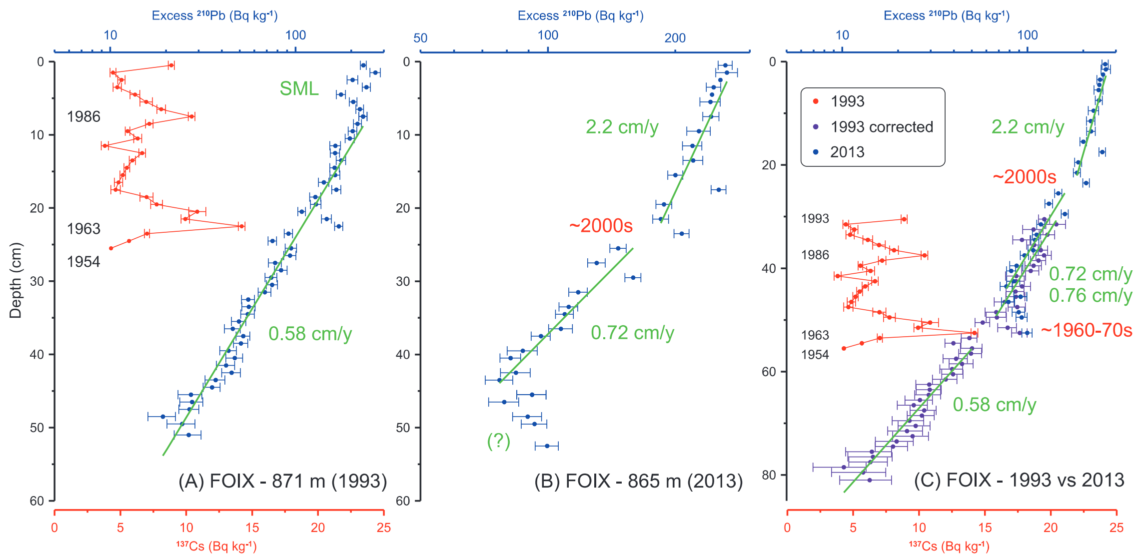


Figure 5. Excess ^{210}Pb and total ^{137}Cs activity profiles of the two sediment cores collected 20 years apart in the Foix canyon axis. A constant sediment accumulation rate was assumed in 1993 by Sánchez-Cabeza *et al.* (1999), while in the sediment core collected in 2013, a noticeable change in sediment accumulation rates was detected circa 2000. The combination of both cores without considering a SML in the 1993 one also suggests a subtle increase of sediment accumulation rates ~1960-70s.

Conclusions and prospects

The analysis of sediment accumulation rates from various sediment cores recently collected along the axes of several submarine canyons of the Catalan margin has evidenced that bottom trawling activities have altered the natural sedimentary dynamics in all studied sites since the 1960-70s. The resulting increase in sediment accumulation rates seems to be limited to canyon regions close to fishing grounds, while deeper areas remain unaffected as a consequence of a predominant along-margin transport of the trawled-induced resuspended particles.

In addition, an even more significant change in sedimentation rates has occurred in specific submarine canyons since the beginning of the 21st century, accounting for values >2 cm y^{-1}. Such enhanced sedimentation rates may seem in contradiction with the slight decrease in total power of the local trawling fleet obtained from the official databases. The reality is that ship-owners have been continuously introducing technical improvements in their trawlers (namely more powerful engines and larger gears), a practice that leaves no trace in the official reports. The official decreasing trend mainly reflects a reduction in the total number of vessels, since a large dismantling of trawlers has been occurring in the Catalan harbors since the 1990s, motivated by subsidies and aids provided by the European Commission to the fishing sector. However, even though the new constructed vessels are officially limited to <500 Hp, their real horsepower is generally much higher.

Together with the not declared increase in installed power, one must take into account that, over the last decades, the Catalan trawling fleet has evolved towards an increasing economic specialization and dependence in the *Aristeus antennatus* fishery (Alegret and Garrido, 2008). This may also contribute to the significant increase of sediment accumulation rates within specific submarine canyons, as a result of progressive concentration of the fishing effort over this species and the subsequent increase in trawling-induced resuspension (and relocation) of sediments surrounding submarine canyons.

Acknowledgements

This work was funded by the HERMIONE and PERSEUS projects (7FP Grant agreements: 226354 and 287600) and the Generalitat de Catalunya grants (2014 SGR 1356 and 1642). We thank the officers and crew of R/V *García del Cid*, and all the participants in the coring surveys for their assistance during ship operations. P. Masqué acknowledges the financial support by a Gledden Visiting Fellowship awarded by the Institute of Advanced Studies at The University of Western Australia.

---

* this chapter is to be cited as:

Puig P., Masqué P., Martín J., Paradis S., Juan-Díaz X., Toro M., Palanques A. 2015. Changes in sediment accumulation rates within NW Mediterranean submarine canyons caused by bottom trawling activities. pp. 71 - 78 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.

A case study on vulnerable marine ecosystems in Cassidaigne Canyon - New technologies to track anthropogenic impact

Marie-Claire Fabri, Annaelle Bargain, Aurelien Arnaubec, Ivane Pairaud, Laura Pedel and Ewen Raugel

Ifremer, Centre de Méditerranée, La Seyne sur Mer, France

Abstract

Canyons are subjects of increasing human exploitation, which calls for increased focused management and conservation attention. The development of appropriate European policies and Marine Protected Areas, including for deep sea habitats, implies the development of adapted monitoring tools and methods to assess benthic-habitat quality in coastal waters and provide spatial information about the extent and composition of vulnerable marine resources also in deep waters as required by the recent European Marine Strategy Framework Directive. This paper reviews several methods that could be used for a benthic-habitat assessment. Vessel monitoring system data could be used to focus monitoring on anthropogenic impacted areas. Multi-beam echo-sounder data and backscatter data classification could be used for the production of reproducible habitat maps based on signal segmentation, provided a high resolution at the acquisition. Side-Scan Sonar and textural analyses may be useful to differentiate bottom types. The use of submersibles designed to manoeuvre in complex topography together with the use of acoustic instrument and HD images for 2D mosaicking and 3D reconstruction help to increase the capabilities to study (and monitor) environments inaccessible up to now. The last method presented in this paper is the production of predictive habitat maps. A case study on the Cassidaigne canyon is shown where protected cold-water coral species co-exist together with heavy anthropogenic impact (red mud discharge).

Introduction

Soft substrate bottoms compose the major part of the deep seafloor. Nevertheless some topographic features may enhance the heterogeneity of continental slopes like submarine canyons. These submarine valleys form part of the drainage system of continental margins. They are major pathways for material and organic carbon transported from the land to the deep sea (Puig *et al.*, 2008). They have been suggested to be hotspots of biological activity and are preferential areas for the recruitment of megafaunal species (Sarda *et al.*, 2004). Canyons probably play an important role in structuring the populations and life cycles of benthic megafauna fishery resources that are associated with them. For example, canyons provide important habitats for fished species, such as hake (*Merluccius merluccius*), red shrimp (*Aristeus antennatus*) and Norway lobster (*Nephrops norvegicus*) (Danovaro *et al.*, 2010). Those commercial resources live within ecosystems that are becoming vulnerable with regard to fishing pressure. Thus canyons may provide a heterogeneous set of habitats, often hosting both Vulnerable Marine Ecosystems and rich fishing grounds, as shown for the Gulf of Lion (Fabri *et al.*, 2014), Which accounts for their listingas key marine habitats by the General Fisheries Commission for the Mediterranean (GFCM, 2009).

Monitoring ecosystems imply measuring and quantifying. Statistical tools previously developed to monitor coastal areas are based on multiple sampling and on the presence or absence of species known for a particular ecological trait reflecting an adaptation to a particular unbalanced environment. However, the complex and steep topography, the locally enhanced currents, the occasional down-canyon flushing events and the hard substrates found in submarine canyons (Mascle *et al.*, this volume) make sampling, surveying and monitoring difficult and did limit early studies.

The objective of this paper is to present the evolution of monitoring methods applied in marine environment as supported by technological advances (e.g. remote sensing techniques, autonomous and remotely-piloted vehicles) and oriented towards the monitoring of ecosystem spatial distribution.

1 - Traditional methods for marine environment and benthic communities monitoring

Mathematic indexes (combination of criteria) provide measurements of anthropogenic impact or progress of restoration efforts in marine environment quality. Indexes based on biological variables are commonly based on the absence of sensitive or the presence of tolerant species and were developed to follow ecosystem response to a gradient of disturbance (e.g. enrichment in organic matter).

The large list of existing indexes is mainly focused on the monitoring of infauna communities living inside the sediment and requires sediment sampling, sorting and taxonomic classification (Diaz *et al.*, 2004). Generally species are grouped according to their ecological traits (tolerant vs sensitive, filter vs deposit feeders). It is noteworthy that the evolution through time went from the development of indexes based on extensive samples in which an exhaustive community identification was realized towards indexes based on a reduced number of species known to be tracers of a disturbance. In submarine canyons extensive samples are not realistic (for time and technical reasons) and most of the species are not described yet (Bouchet, 2006), and so an indirect measurement of a disturbance using a limited number of known species is the common way to monitor infauna (Fontanier *et al.*, 2012; Amaro and Kiriakoulakis, this volume).

The study of fragile epifauna communities living erected on the bottom (e.g. sponges and gorgonians) requires non destructive optical techniques. Indexes based on optical images have been developed, taking advantage of the recent access to waterproof cameras available to the general public. Very few indexes exist to measure community statements from optical images, and they were mainly developed in the coastal and photic zone (0-60 m) (Ballesteros *et al.*, 2007; Creocean, 2009; Deter *et al.*, 2012; Gatti *et al.*, 2012; Seytre and Francour, 2008). The use of non destructive methods to monitor deep-sea ecosystems such as engineer species providing a structural habitat, a refuge and food to other species and recently exposed to anthropogenic pressure is a new challenge for research.

2 - Towards monitoring the spatial distribution of benthic deep-sea communities

Recent advances in seafloor technology (e.g. the development of autonomous and robotic vehicles, new *in situ* measurements techniques) create new opportunities for seafloor observation in the challenging deep-sea environments. They significantly increase the accessibility of submarine canyons, and provide tools to achieve a new break-through in deep-sea communities monitoring.

Soft substrate bottoms compose the major part of the deep seafloor. Nevertheless even if some topographic features may enhance the heterogeneity of continental slopes like submarine canyons, an exhaustive monitoring is not realistic in the deep sea. Areas known for their anthropogenic pressure need to be targeted for an efficient monitoring.

• Vessel Monitoring System data

Vessel Monitoring System (VMS) data can be used in order to highlight areas of heavy fishing pressure. The VMS is a satellite-based monitoring system which at regular intervals (http://www.marinetraffic.com) provides data to the fisheries authorities on the location, course and speed of vessels longer than 15 meters.

These data gathered by year indicate heavy pressure areas (Martin *et al.*, 2014) and probably the location of the original facies linked to the corresponding resources (*Funiculina quadrangularis* sheltering Norway lobster and *Isidella elongata* sheltering red shrimps). These original facies may have been swept away by repeated trawling as observed in the adjacent canyon off the Spanish coasts (La Fonera canyon, off Spain) (Martín *et al.*, 2014a). In that example multi-beam echo-sounder data were used to evidence the smoothering action of trawlers on the seafloor modifying the morphology of the sea floor above 800 m (Puig *et al.*, 2012; Pusceddu *et al.*, 2014; Puig *et al.*, this volume).

It is not known whether anthropogenic pressure is as intense in the Gulf of Lion since VMS data are not available from the French government. The idea to use Spanish VMS data to follow Spanish fleet fishing in the Gulf of Lion would allow to focus on heavily pressurized areas and define which part of the Gulf of Lion canyons could be investigated with new technics (high resolution data, access to quantitative data).

• High resolution Multi-Beam Echo-Sounder (MBES) and backscatter data classification

Up to now the use of AUV or ROV has focused on specific geological morphology (e.g. hydrothermal vent, fluid seepage and mud volcanoes) detected from a previously-built large bathymetry collected from a ship. Submersible embark a scientific pay load and travel along a predefined transect to build a high resolution map.

A monitoring objective would be to launch a submersible in an autonomous mode to cover a large surface on soft substrate where meadows of Vulnerable Marine Ecosystems have been described to live on in the past in order to measure the extent of the habitat (ecosystem) or to detect anthropogenic impact. Increased resolution is the key to discriminate habitats using either bathymetric or backscatter data.

Facies classification based on backscatter data from high-resolution MBES is a technique commonly used for substrates (Dupre *et al.*, 2010; Vertino *et al.*, 2010) and starting to be used for biological habitats (Micallef *et al.*, 2012b). Automatic segmentation, opposed to expert interpretation, of backscatter data together with ground-truth sampling or video data could help to the development of fast and repeatable methods of seabed classification for an efficient monitoring with regard to environmental and anthropogenic impact assessments (Stephens and Diesing, 2014).

• Side-scan sonar and textural characteristics

When seafloor cannot be differentiated on the basis of acoustic backscatter, a textural analysis from side-scan sonar may be useful to differentiate bottom types. Side-scan sonar data are used in the interpretation for the construction of geological maps (Cochrane and Lafferty, 2002; Greene *et al.*, 2013; Kaeser *et al.*, 2013). These data are generally of high quality and facilitate interpretation of the textural characteristics. Side-scan sonar has also been demonstrated to allow observation of trawl damage (Darwin Mounds, NE Atlantic) at almost 1000 m water depth as well as the decrease in coral abundance (Roberts *et al.*, 2006).

The use of high-resolution side-scan sonar data could be a way to map and measure the extent of erected megafauna species meadows (e.g. *Funiculina quadrangularis* and *Isidella elongata)* as they should induce a difference in the sediment texture compared to flat sediment areas. In a monitoring purpose the advantage would be to benefit from the automatic segmentation that could be used on a large area (as opposed to a manually drawn classification from a video mosaic). A temporal evolution of the spatial extent of large scale ecosystems could be monitoring based on high resolution signals.

• Autonomous and robotic vehicles (e.g. Hybrid Remote Operated Vehicle)

The ever increasing demand for biological and acoustic data of the underwater environment has prompted the French oceanographic institute IFREMER to design a new vehicle to meet novel scientific exploration challenges (Brignone *et al.*, 2013). The main objective of this hybrid underwater robotic system (HROV Arianne) is to combine the ability to gather high resolution data and perform inspection and intervention tasks while maintaining operational costs to a minimum. This will enable wider access by the scientific community to highly specialized vehicles designed to meet their goals.

The implementation of this new underwater vehicle responds to novel challenges in oceanographic science. The scientific community needs to explore and perform intervention tasks in natural environments where morphology presents obstacles to existing underwater vehicles. Such environments include underwater canyons, seamounts, ridges rift valley walls and continental margins, where the predominantly rocky or hard substrate favors the development of rich faunal settlements. The new vehicle that will join the Institute's operational fleet in 2016 precisely targets mapping, sampling and monitoring tasks through the implementation of a hybrid architecture to bridge between canonical ROV and AUV systems (Fig. 1).

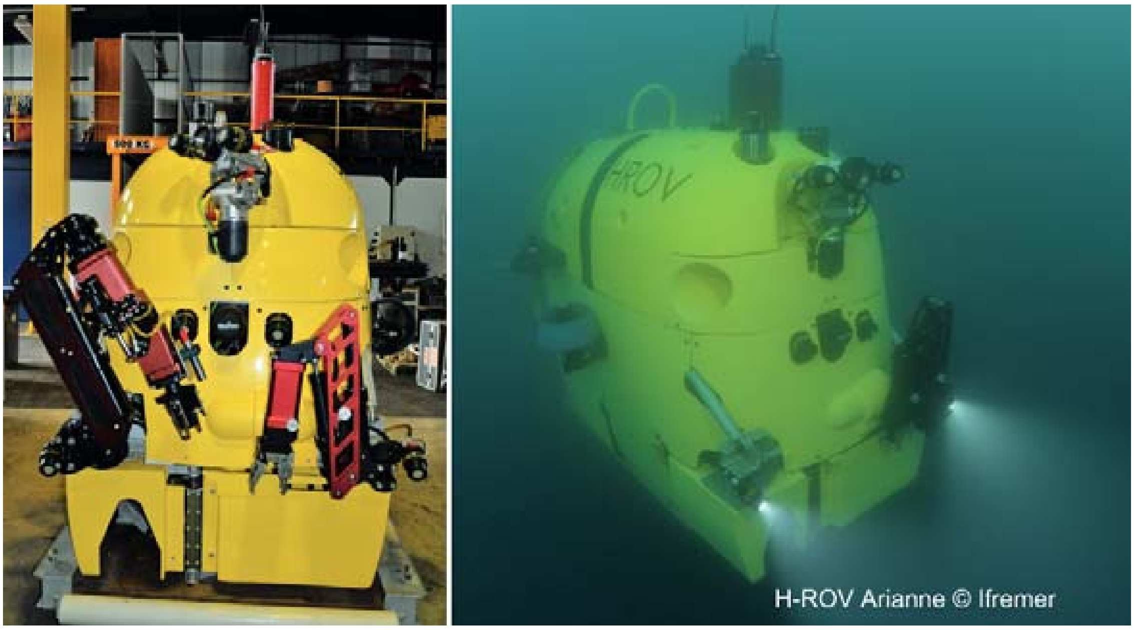


Fig. 1. Hybrid ROV Arianne (Ifremer) available to the scientific community from 2016 is designed to navigate in uneven and rough environments such as canyons.

H-ROV Arianne is a LiIon battery operated underwater system that can be configured and operated in tethered (ROV) or autonomous (AUV) modes. The vehicle's weight (1.8 tons in tethered configuration, 1.6 tons in autonomous) and dimensions (2.5m x 1.8m x 1.2m) are compatible with operation from small vessels. The operational maximum depth for the vehicle is set to 2500m.

With the objective to cross reference optical and bathymetric maps of the seafloor with samples collected *in situ* and surveys to be repeated over time in order to measure the temporal evolution of the ecosystems spatial extents, navigation performances fulfill several goals such as cruising at a constant speed and altitude as well as keeping a fix position and being accurately located. Intrinsic stability is required to facilitate precise manipulation which is performed with two electrical manipulators. A motorized basket allowing to carry down a sampling box and four tube cores as well as a suction sampler (6 bowls) fixed on the structure are available for the scientific community working for the H-ROV Arianne.

• Photos and videos for 2D mosaics and 3D reconstruction

Species or ecosystems spatial distribution assessment from optical images is available in the deep sea since recent technologies allow scientists to use submersibles, waterproof cameras and geo-referenced data. Video and image sampling provide a non-destructive alternative to physical sampling but are subject to a number of challenges among which the identification of taxa without physical specimens. High Definition image quality is highly recommended in order to see the defining characteristics allowing a species to be recognized on images or video films with no misidentification (Howell *et al.*, 2014). HD video survey data collected along transect lines for use in ecological data analysis may be gathered into a geo-referenced 2-dimension mosaic so as to facilitate cartography of ecosystem spatial distribution (usually a vertical camera orthogonal to a flat horizontal bottom) (Fabri *et al.*, 2011). A mosaic created at regular interval enables a temporal monitoring of the spatial extent of an ecosystem on flat bottoms (Marcon *et al.*, 2014; Olu-Le Roy *et al.*, 2007). Most of 2D algorithms suppose that the seafloor does not present strong variations and that scene is seen from the top.

This is hence a challenging issue to perform mosaicking of vertical cliffs, or of any complex structure having both horizontal and vertical surfaces. The first challenge is in the acquisition process. For this purpose a digital tilt-camera has been mounted on the H-ROV Arianne (Fig. 2).

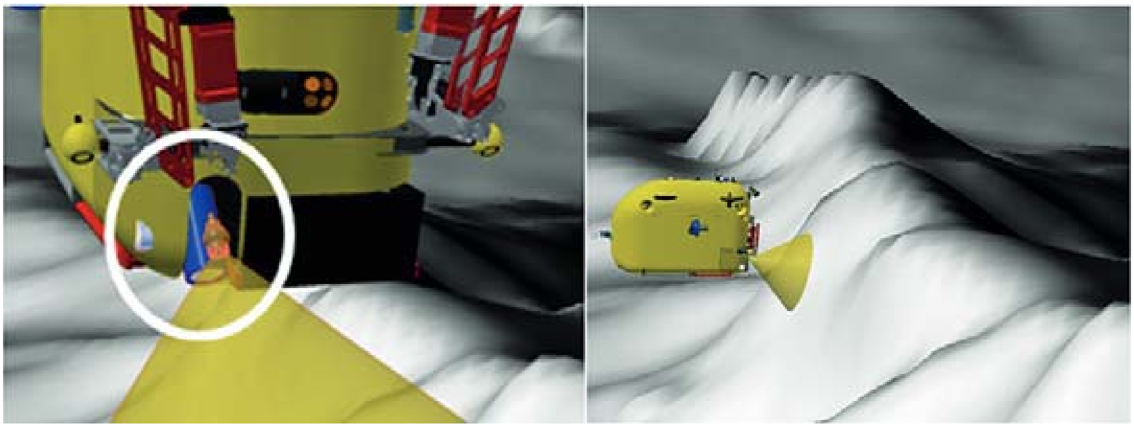


Fig. 2. A tilt-mounted digital camera (Nikon 5100) will be available on H-ROV Arianne (Ifremer) to create photo mosaics of vertical structures.

Then, with the appropriate acquisition, images will be processed through a 3D model of the scene (using 'structure from motion' techniques) (Bruno *et al.*, 2011; Nicosevici *et al.*, 2009). For that purpose, video films or still images need to be recorded in repeated transects allowing several views of the objects (e.g. north, south, east, west views). These requirements should be easily fulfilled in the future with the very easy-to-handle H-ROV Arianne. This will enable to reconstruct 3D textured geo-referenced scenes through non-destructive measurements.

Hard bottom substrates often display complex structures for which 3-dimension mosaics can bring supplementary information on the species layout and arrangement with regard to predators, currents or silting exposure for instance.

• High resolution Multi-Beam Echo Sounder (MBES) data and predictive habitat models: A case study in the Cassidaigne canyon

The increasing need to manage and protect vulnerable marine ecosystems has motivated the use of predictive modeling tools, which produce continuous maps of potential species or habitat distribution from a limited number of observation points and full coverage environmental data. Predictive habitat mapping is quite a recent way of working at population scale, taking advantage of the spatial information brought by MBES technologies.

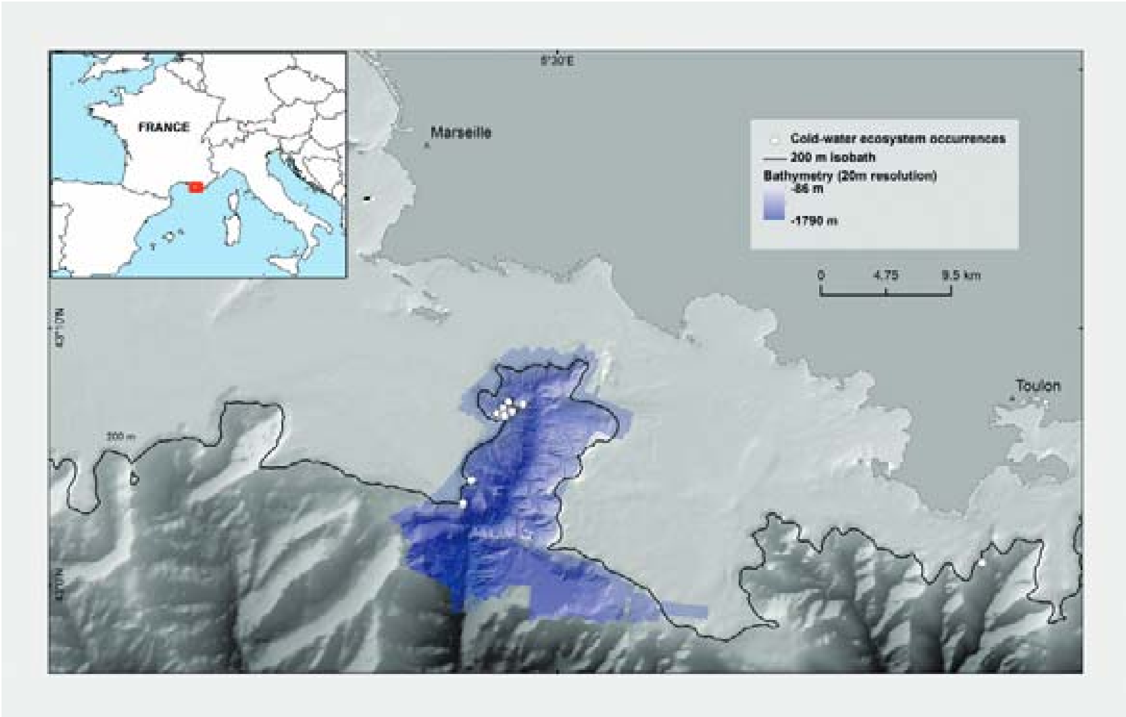


Fig. 3. Location of the Cassidaigne canyon in the North-Western Mediterranean Sea. The high resolution bathymetry coverage and Cold-Water Coral distribution used for the predicting habitat model are shown (from Fabri *et al.*, 2014).

Study area and issues

The Cassidaigne submarine canyon is the largest of the Provence coast between the Gulf of Lion and the Ligurian Sea, between Marseille and Toulon (Fig. 3). This canyon consists of an incision up to 1700 m deep and 20 km long, located 8 km south from the coast. The general water circulation is westward along the continental slope and is constrained by two dominant winds: north-northwest winds (upwelling favorable winds) and southeast winds (downwelling favorable winds). Prevailing winds from north-west to west (Mistral) induce a displacement of surface waters to the open sea, generating six upwellings in the Gulf of Lion (Millot, 1990). In relation to wind and coast-line direction and, possibly, to the presence of the canyon, the most intense upwelling of the Gulf of Lion is centered within the Cassidaigne canyon off Marseille (Alberola and Millot, 2003).

This canyon is a preferential habitat for the cold-water coral species *Madrepora occulata* which form colonies supported by a common skeleton, providing a structural habitat for other species and identified as a sensitive habitat of relevance for the management of priority species in the Mediterranean Sea by the General Fisheries Commission for the Mediterranean (GFCM, 2009). Their spatial distribution is of concern for the Marine Strategy Framework Directive.

The Cassidaigne canyon has received red mud discharged by the Gardanne Aluminium factory since 1967 (Dauvin, 2010; Fontanier *et al.*, 2012). From 1967 to 1988, during 21 years, a massive disposal of bauxite residues coming from two pipelines at 320 m depth from two separate factories affected the canyon. Since 1988 red mud discharge was reduced as one factory stopped production. The entire seabed along the canyon axis was covered by red mud below 350 m depth. The red mud also draped steep inclined rock exposures and was found underneath overhangs (Fabri *et al.*, 2014). The objective to stop the outflow by 2015 (this year!) would certainly help cold-water coral species to survive.

The episodically severe up- and down-welling current regimes may be the driving force for the complete spatial coverage of the natural seabed by man-made discharges, but also for the settlement of CWC in the Cassidaigne canyon. Predictive habitat mapping in this canyon will allow to better understand the spatial distribution of cold-water coral population, as in the Cap de Creus canyon in Spain (Lo Iacono *et al.*, this volume).

Material

Occurrences of CWC colonies (*Madrepora occulata*) were plotted in a GIS from video records (using Adelie-GIS and Adelie Video ©Ifremer) collected during 4 cruises (ESSROV 2010 with Victor 6000 ROV from Ifremer, MEDSEACAN 2009 with Achille ROV from Comex, MARUM 2009 with Achille ROV from Comex, ESSNAUT 2013 with Nautile from Ifremer).

Seafloor characteristics (e.g. slope, curvature, eastness, northness, rudgness, bathymetric position index, etc.) were extracted using ArcGIS from the 10-meter resolution bathymetric data (RESON Seabat 7150 multibeam echosounder (24 kHz)) collected during ESSROV 2010 cruise.

In order to get the environmental conditions in the CWC habitat areas, the MARS3D (Lazure and dumas, 2008) hydrodynamic model (in its version V10.2) was set up in the Cassidaigne canyon over the period September-December 2013 (for another example of hydrodynamic model see Carniel *et al.*, this volume). The CASCANL configuration uses a 170x197 mesh grid at a horizontal resolution of 400 m, and 60 vertical generalized sigma levels (for which the levels are refined close to bottom and surface). The general circulation forcing at open boundaries is provided by the operational MENOR model configuration of the NWMED (Garnier *et al.*, 2014). The atmospheric forcing (wind, heat fluxes, rain) is provided by the ARPEGE (Meteo-France) model. Thanks to a refined bathymetry at 10m resolution, a two-way nesting is operated in the CASCANL configuration, with an embedded zoom at 80 m horizontal resolution centered on the canyon (CASCANS configuration). This nesting is performed using the AGRIF (« Adaptive Grid Refinement In Fortran ») tool (Debreu *et al.*, 2008), and enables to take into account the effect of fine scale bathymetry over bottom currents and retroactions over larger scale. Comparisons of model results with satellite images (ocean color and sea surface temperature) and *in situ* data (hydrology and current) were performed in order to validate the model, both in terms of processes (through their physical signature patterns) and statistically (through quantitative comparisons at fixed stations or along vessels transects). The model provides hourly information on the hydrology (temperature, salinity, density) and dynamics (currents) of the area. The first sigma levels near sea bottom (roughly 10 meters) were considered for the predictive habitat mapping.

Methods

A statistical model is used to relate observed species distribution to seafloor characteristics and environmental conditions near bottom (10 m) and to determine the contribution of each variable to the species distribution. Three groups of statistical methods commonly used to discriminate which of the environmental parameters influence the ecosystem distribution will be tested on the study area.

- The Ecological-Niche Factor Analysis (ENFA) is based on the niche concept and compares, in the multidimensional space of ecological variables, the distribution of the localities where the focal species (only one species at a time) was observed to a reference set describing the whole study area (Hirzel *et al.*, 2002; Hirzel and Le Lay, 2008). This model determines the marginality (preference for specific conditions) and specialization (narrowness of the niche envelope) of the species regarding to each variable.

- The maximum entropy method (MAXENT) is a general approach for modeling species geographic distributions with presence-only data. Maxent is a general-purpose machine-learning method in which the idea is to estimate a target probability distribution by finding the probability distribution of maximum entropy (i.e., that is most spread out, or closest to uniform), subject to a set of constraints that represent the incomplete information about the target distribution (Elith *et al.*, 2011; Phillips *et al.*, 2006).

- Generalized Linear Models (GLM) and Generalized Additive Models (GAM) are multiple regressions often used for modeling species distributions with presence–absence datasets together with stepwise selection of predictors (Guisan and Zimmermann, 2000). They are based on an assumed relationship (link function) between the response variable (occurrence of CWC) and the explanatory variable (seafloor & environmental data). GLMs are based on linear regressions but allow for non-linearity and non-constant variance structures in the data. GAMs are semi-parametric extension of GLMs, their strength is their ability to deal with highly non-linear and non-monotonic relationships between the response and the set of explanatory variables (Guisan *et al.*, 2002).

The two first groups (ENFA and MAXENT) present the advantage of requiring only presence data, a frequent situation in the case of animal observations where absences are difficult to assess in the field (e.g. mobile or hidden species). The last group (GLM/GAM) based on presence and true-absence data should be more robust (results are under process).

Preliminary Results and Discussion

Our first attempts in using ENFA and MAXENT models evidence three parameters influencing the distribution of *Madrepora occulata*: water density, bottom rugosity and current speed. These results need to be confirmed using regression models (GLM /GMA). Statistical model results will be used to produce habitat suitability maps of the potential local distribution. Localities selected by the models for being probable habitats for CWC should be visited for ground-truthing in order to validate the model and eventually extend the actual protected area. Absence of species at selected localities of course will be attributed to anthropogenic impact and red mud discharge in this canyon. The objective to stop the outflow by 2015 should help CWC inrecovering their original distribution. Predictive habitat maps will guide future monitoring of cold-water corals and help assess their spatial recovery when not too late.

The potential predicted distribution may be larger than the effective distribution, generally due to biotic interactions (e.g. interspecific competition or predation) or geographic barriers that have prevented dispersion or colonization or human influence (anthropogenic impact). These modeling methods help in predicting suitable habitats for vulnerable marine species or ecosystems to support conservation planning and marine protected area network design.

Conclusion

Autonomous and remotely-piloted underwater vehicles, high-resolution acoustics techniques and high-definition images increase the efficiency with which benthic habitat maps are produced. They should become dynamic monitoring tools permitting (1) the production of synoptic maps that integrate useful information needed to detect a perturbation (2) the use of semi-automatic segmentation to produce efficient and reliable classification to create habitat maps and reduce the amount of manual editing (3) a frequent and reproducible assessment of the spatial distribution of a community to evidence a response to a perturbation (4) the development of accurate predictive habitat maps which constitute invaluable tool for conservation management. All these technologically-based methods could be efficiently applied at an ecological scale on condition that the resolution is provided at a meter scale.

---

* this chapter is to be cited as:

Fabri M.C., Bargain A., Arnaubec A., Pairaud I., Pedel L., Raugel E. 2015. A case study on vulnerable marine ecosystems in Cassidaigne Canyon - New technologies to track anthropogenic impact. pp. 79 - 86 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.

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

Claudio Lo Iacono[1], Mauro Agate[2], Attilio Sulli[2], Matthieu Cartigny[1], Katleen Robert[1], Andrea Gori[3] and Tommaso Russo[4]

[1] *National Oceanography Centre, Marine Geoscience, European Way, UK*
[2] *University of Palermo, Dpt. of Earth and Sea Sciences, Palermo, Italy*
[3] *Universitat de Barcelona, Dpt. of Ecology, Barcelona, Spain*
[4] *University of Rome Tor Vergata, Dpt. of Biology, Roma, Italy*

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),

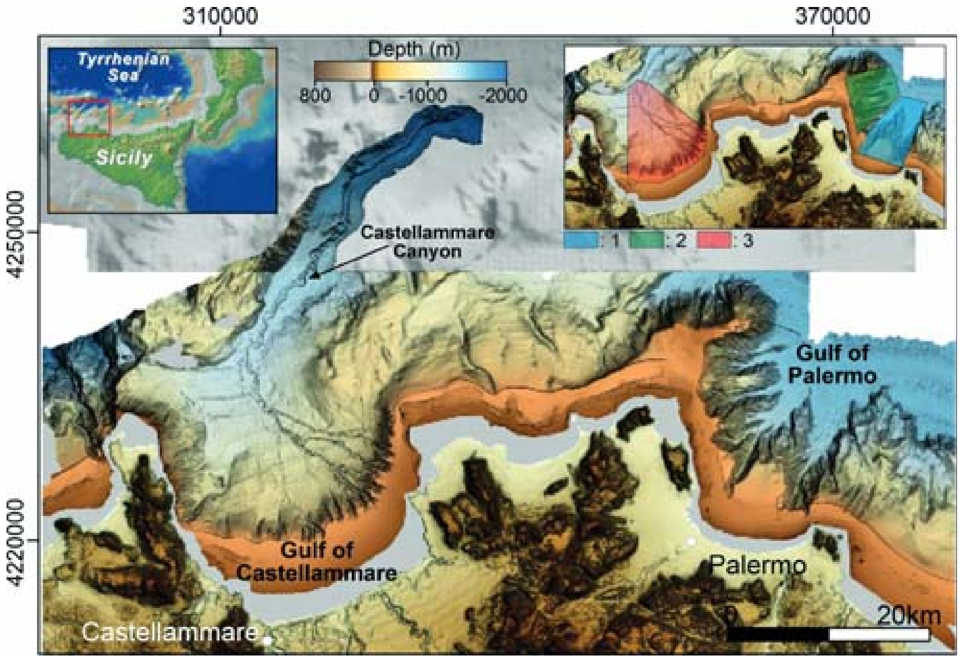


Figure 1. Multi Beam bathymetric model of the NW Sicilian Margin, showing the two main canyon systems described in this paper. The three different colored areas in the top-right inset correspond to the three canyon system types described in the section.

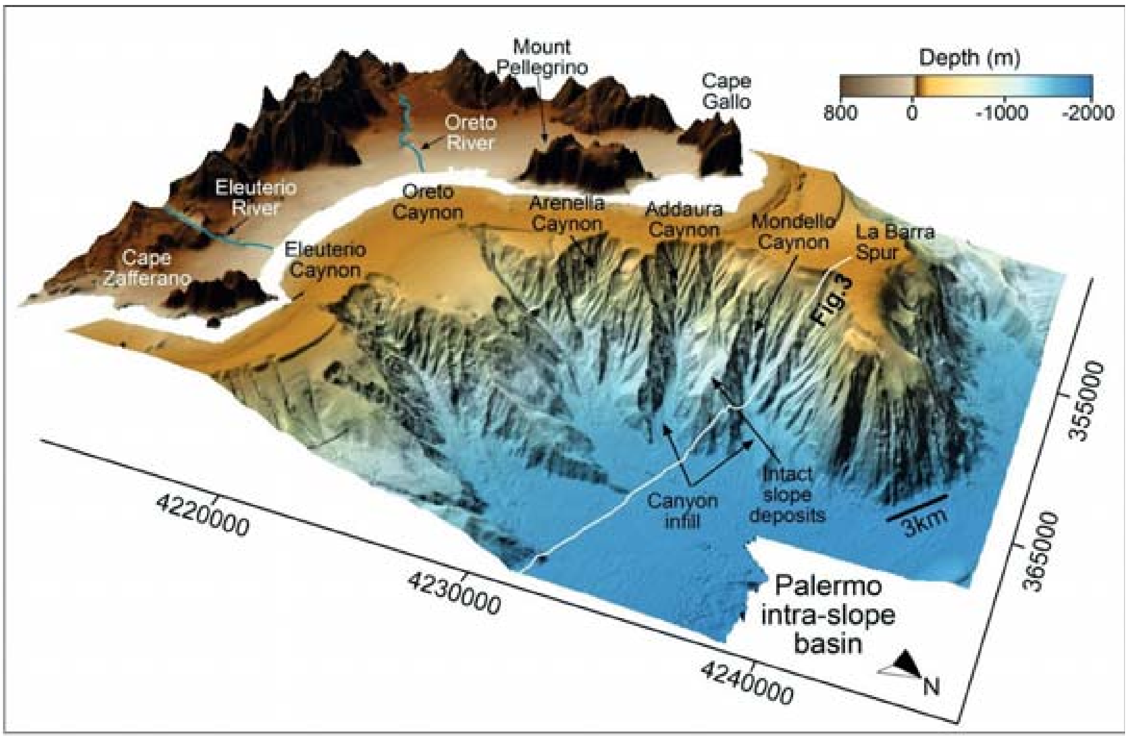


Figure 2. Multi Beam 3D model of the Palermo canyon system.

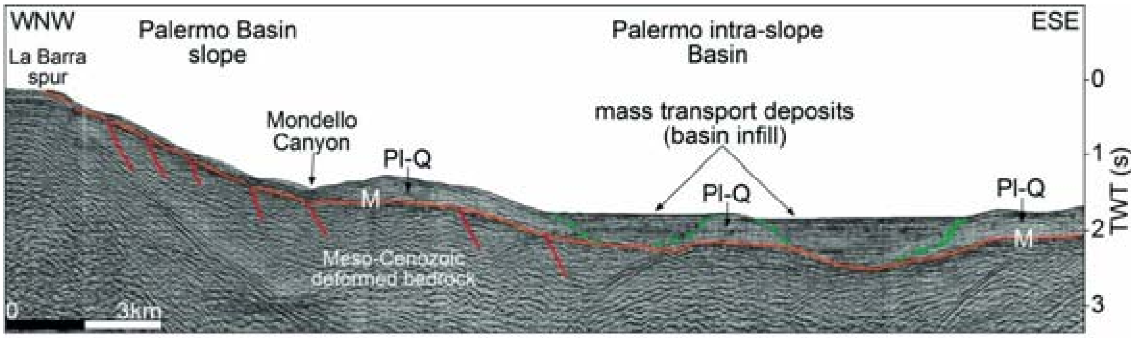


Figure 3. MCS profile crossing the Palermo Basin.

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.

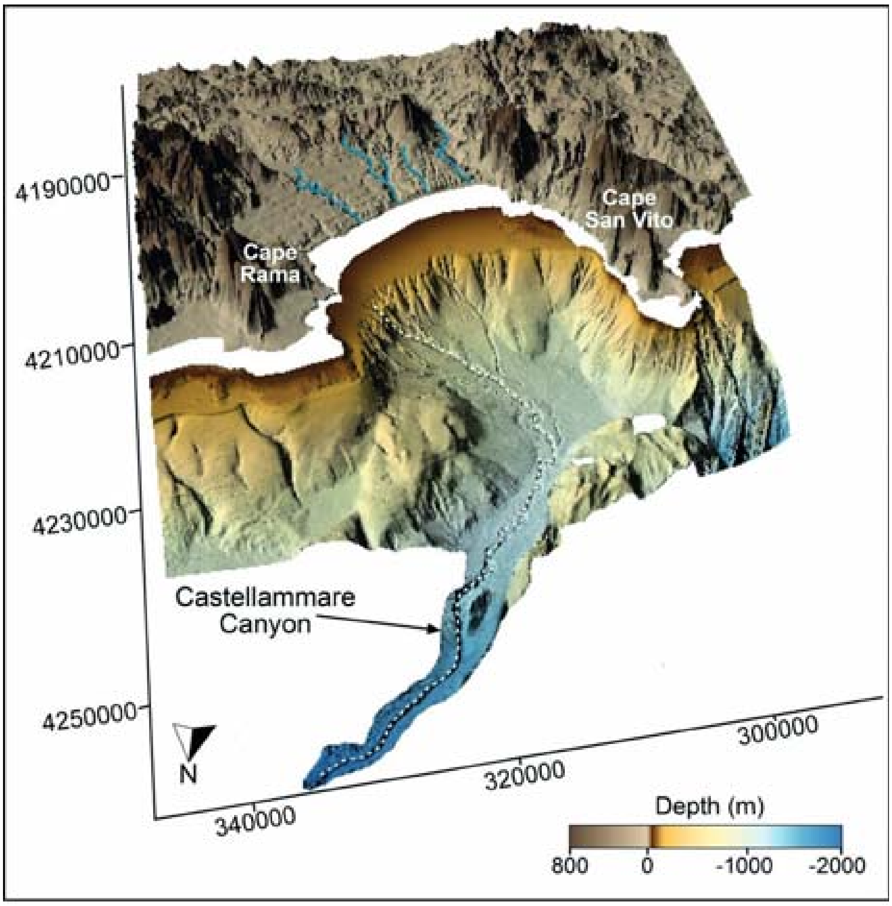


Figure 4. Multi Beam 3D model of the Castellammare Canyon.

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

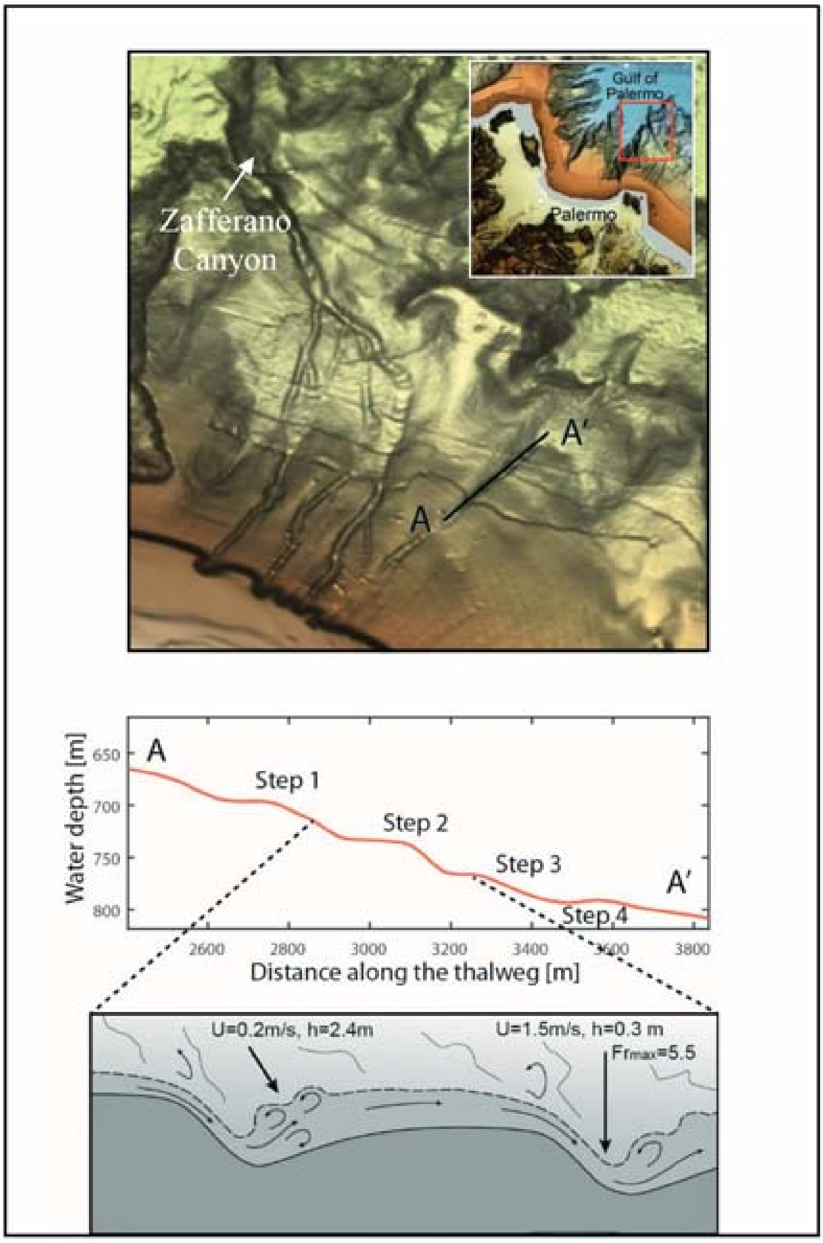


Figure 5. Cyclic steps along the gully network of the Zafferano Canyon. Bathymetric profile crossing the most pronounced cyclic steps and estimation of genetic flows based on numerical modelling.

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.

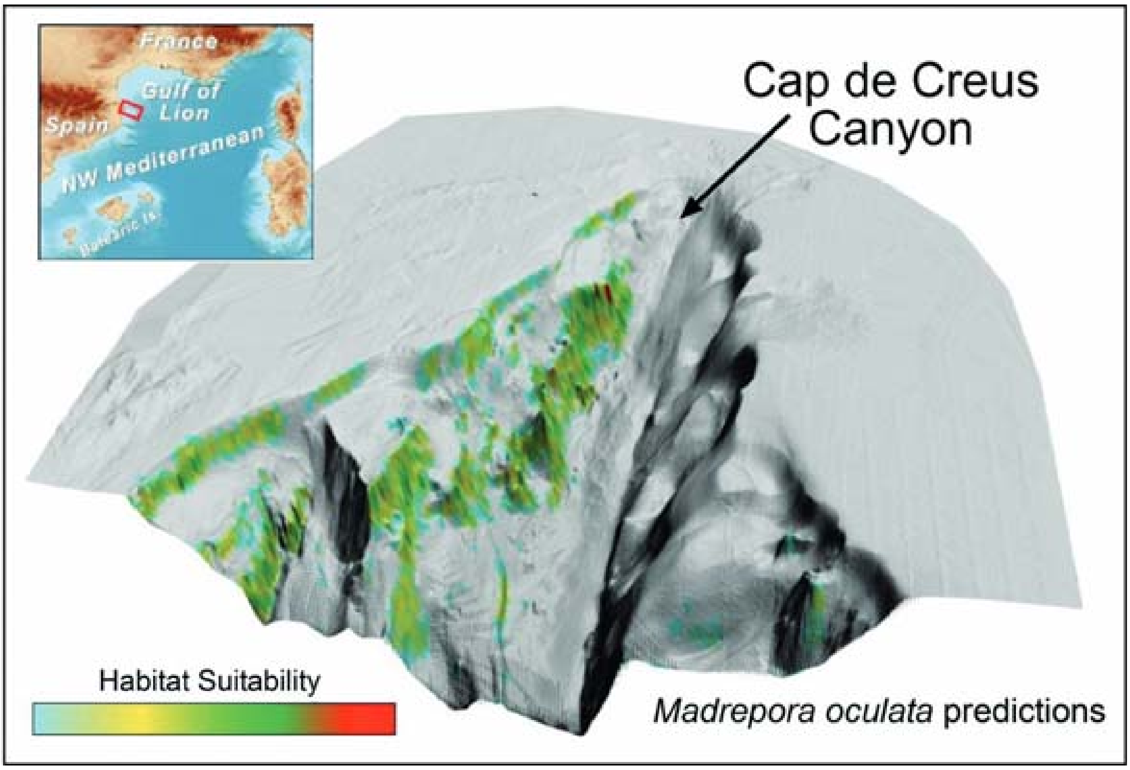


Figure 6. Predictive ensemble map (50 m resolution) for *Madrepora oculata* distribution in the Cap de Creus Canyon.

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.

---

* this chapter is to be cited as:

Lo Iacono C., Agate M., Sulli A., Cartigny M., Robert K., Gori A., Russo T. 2015. Development, human impact and habitat distribution in submarine canyons of the Central and Western Mediterranean. pp. 87 - 96 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.

Organic matter transport and deposition in the Whittard Canyon and its possible effects on benthic megafauna

Teresa Amaro[1] and Konstantinos Kiriakoulakis[2]

[1] *Hellenic Center for Marine Research (HCMR), Heraklion Crete, Greece*
[2] *John Moores University, School of Natural Sciences and Psychology, Liverpool, UK*

Abstract

The Whittard Canyon (NE Atlantic) is one of the largest canyon systems on the northern Bay of Biscay margin. It likely receives a high input of organic matter from the productive overlying surface waters, and part of this organic matter may eventually be transferred down the canyon into the Whittard Channel extending from the canyon mouth onto the Biscay Abyssal Plain. In this study we re-examine and integrate the current knowledge on the possible transfer of organic matter through this canyon and its effects on the megafauna communities. We show that the canyon-mediated transport of OM can provide favourable environmental conditions (current regime, food input) to sustain megafauna communities, but that at greater depths other mechanisms can also be important. The insights obtained here contribute to our wider understanding of submarine canyons in general.

1. Introduction

Submarine canyons are large geomorphological structures that incise continental shelves and steep slopes along continental margins. They can be highly dynamic sedimentary environments where sediments rich in organic matter (OM) are trapped or transported downslope across the shelf and slope to greater depths (e.g. Rowe *et al.*, 1982; Hecker, 1990; Duineveld *et al.*, 2001;Tyler *et al.*, 2009; De Stigter *et al.*, 2007; Garcia *et al.*, 2010; Canals *et al.*, 2013; Puig *et al.*, 2012). This capacity enriches the canyon ecosystem and has profound consequences on the biota (Maurer *et al.*, 1994; Vetter and Dayton, 1998; Ingels *et al.*, 2009; De Leo *et al.*, 2010; Amaro *et al.*, 2010; Huvenne *et al.*, 2011). When compared to adjacent areas of the continental slope, canyons are up to 30 times more effective in burial of organic carbon (e.g. Nazaré Canyon, Masson *et al.*, 2010; Pusceddu *et al.*, 2010). For instance, the presence of frenulate siboglinids and thyasirid bivalves (typical organisms from chemosynthetic environments) in canyon sediments is indicative of high organic loading (Cunha *et al.*, 2011). Canyons also play an important role in feeding and reproduction of a broad range of benthic and demersal species (Vetter *et al.*, 2010) as there is enhanced food availability in these areas. They provide important habitats for various life stages of benthic and demersal fishes and invertebrates along continental margins and they constitute important sources of larvae for surrounding habitats (Vetter and Dayton 1998, 1999; Company *et al.*, 2008). As a result, submarine canyons have often been termed hotspots of biomass, abundance, metabolic activity and carbon mineralisation when compared to the adjacent slope at comparable depths (Vetter, 1994; Tyler *et al.*, 2009; Amaro *et al.*, 2010; De Leo *et al.*, 2010).

Submarine canyons are also one of the most heterogeneous habitats in the deep sea. They typically encompass a range of sub-habitats, reflecting their topographic and geomorphological diversity. This high degree of heterogeneity supports abundant and diverse burrowing, epibenthic mobile and sessile faunal communities of all size classes. Nevertheless, each canyon is a unique system with a large degree of heterogeneity (McClain *et al.*, 2010).

The Celtic margin situated in the NE Atlantic is incised by a large number of submarine canyons (Fig. 1). The comparatively productive waters overlying this area supply the deep-sea sediments with high levels of OM and carbon (Lampitt *et al.*, 1995; Longhurst *et al.*, 1995; De Wilde *et al.*, 1998; Joint *et al.*, 2001). It seems likely that the canyons on the Celtic margin concentrate part of this export and are important focal areas for budgeting carbon fluxes.

The Whittard Canyon is one of the large canyons on the Celtic margin and has recently become the object of detailed investigations. As a large and dendritic canyon system, with multiple branches converging into a single deep-sea channel extending onto the Biscay Abyssal Plain, and situated below comparatively productive surface waters supporting a high export flux of OM, the Whittard Canyon seems the ideal focal area for concentrating OM fluxes on the continental margin. Whilst the Whittard Canyon has recently become the object of detailed investigations, information on its physical functioning and its ecosystem is still limited (Reid and Hamilton, 1990; Duineveld *et al.*, 2001; Duros *et al.*, 2011; Huvenne *et al.*, 2011; Ingels *et al.*, 2011). Following earlier observations indicating relatively rich benthic life in the Whittard Canyon (Duineveld *et al.*, 2001), we seized the opportunity to provide an overview of the current knowledge in the Whittard Canyon, focusing our paper on the OM transfer through this canyon and its effects on the megafauna communities.

2. Site description

The Whittard Canyon is a large dendritic canyon system that lies in the continental slope off the Celtic margin between the Goban Spur and the Meriadzek Terrace (Fig. 1). The canyon system extends from the upper slope around the 200 m isobaths to down-slope into larger channels onto the abyssal plain. The upper part of the canyon is a complex system of smaller canyons and valleys distinctly V-shaped in cross section and narrow thalweg. The width of the canyon falls to 700 m, with the sidewalls attaining a height of 800 m. The main canyon branches form the middle and lower canyon, are more U-shaped in section and have a broader thalweg. Towards the abyssal plain the height of the side walls reduces to about 100 m (Reid and Hamilton, 1990). The westernmost branch of the Whittard Canyon is the longest, with an along- channel length of 160 km. At almost 4000 m depth, all branches come together at the foot of the continental slope. Beyond 4000 m the canyon continues as a single broad valley that gradually descends for another 150 km to the Biscay abyssal plain at 4300 m depth (Zaragosi *et al.*, 2000).

On the abyssal plain the Whittard Canyon continues as a meandering channel. Together with the Shamrock Channel it constitutes the main tributary of the Celtic Fan, a deep-sea fan fringing the continental margin, fed by sediments originating from the shelf and adjacent land masses and funneled through submarine canyons down the continental slope. The morphology of the Celtic Fan and its tributary channels is described in detail by Zaragosi *et al.* (2000), on the basis of multibeam and 3.5 kHz seismic data and sediment cores. The Whittard Channel starts at the base of the continental slope at about 4100 m depth, where it connects to the mouth of the dendritic Whittard Canyon system. From there it descends along a sinuous course in Sth to SE direction for about 100 km until the junction with the Shamrock Channel at about 4600 m. Further downstream the single channel splits up in a number of smaller and less distinct channels in the middle fan area. The Whittard Channel is 2.5-3 km wide, with 70-150 m of relief from the channel floor to the right levee crest. Levees bordering the channel are strongly asymmetrical; the right levee named Whittard Ridge is 60 km wide and covered with sediment waves, while the left one is less than 10 km wide. On the basis of analyses on cores collected from the fan, Zaragosi *et al.* (2000) concluded that frequent low-density turbidity currents were predominant during the last glacial lowstand and rise of sea-level, whilst during high sea-level conditions hemipelagic deposition prevailed, punctuated only occasionally by high-density turbidity currents and/or non-cohesive debris flows. Current meter observations by Reid and Hamilton (1990) suggest that the present-day environment is characterized by weak bottom currents, too weak to resuspend and transport sediments from the seabed. Yet, Duineveld *et al.* (2001) found indications for biological enrichment in the Whittard Canyon extending to the lower canyon reaches, which they attributed to lateral transport of fresh OM down the canyon.

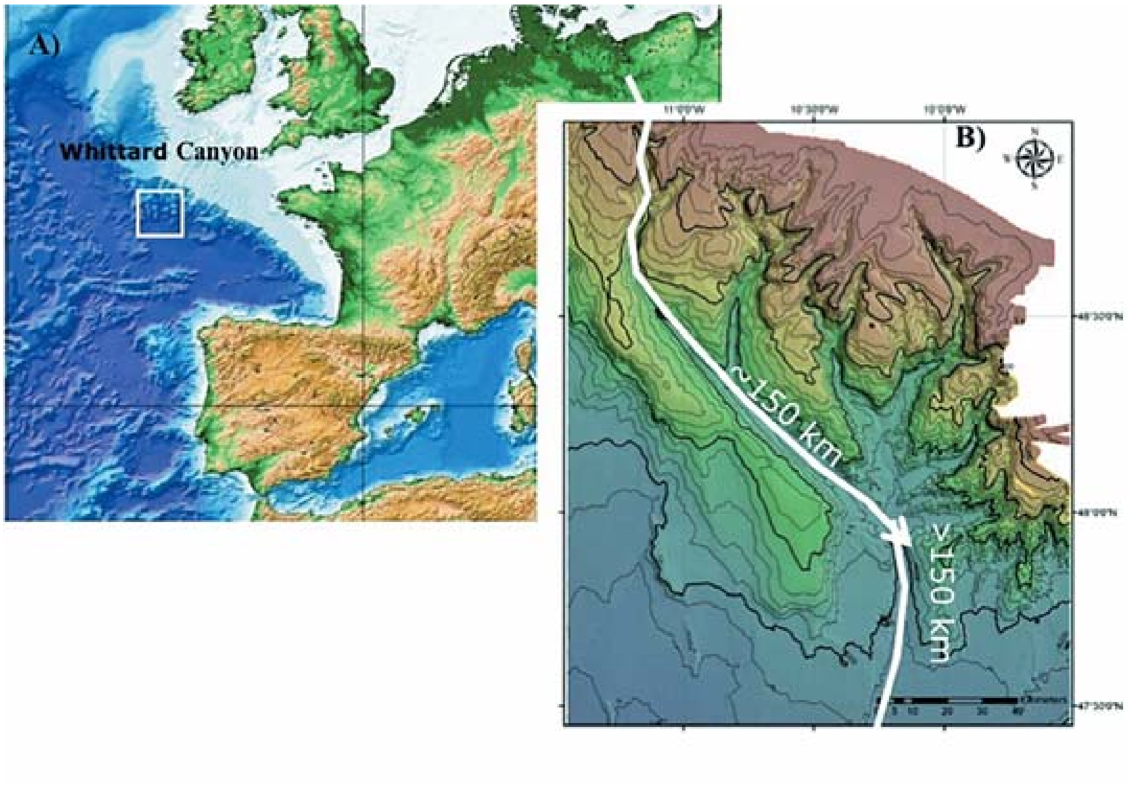


Figure 1. The Whittard Canyon (A) Location of the study area on the western European continental margin; (B) Multibeam bathymetric map of the lower Whittard Canyon and proximal part of the Whittard Channel. Bathymetry courtesy HMS Scott.

3. Organic matter

3.1. Suspended particulate matter (sPOM)

There have been very few studies examining concentrations and composition of suspended particulate organic matter (sPOM) in the Whittard Canyon. Near bottom (<10 m above bottom) sPOM collected using stand-alone pumps in Huvenne *et al.* (2011) were 2 to 3 times higher in the upper parts of the canyon at the far western and eastern branches (> 2000 m depth; one station at each end) than at the deeper (three stations < 3000 m depth) more central parts. The observed decrease in sPOM concentrations with water depth was also a common feature in both cases, attributed to the less energetic nature of oceanographic conditions at the deeper parts. sPOM in that study seemed to be fresh phytoplankton-derived as suggested by the low molar C/N ratios (4.1 – 7.7). In addition the same authors showed that the nutritional quality of sPOM was higher in the upper parts, as evidenced by the elevated concentrations of essential fatty acids, docosahexaenoic fatty acid (DHA) and eicosapentaenoic fatty acid (EPA) in sPOM. EPA and DHA are biosynthesized primarily by phytoplankton and they are pivotal in aquatic ecosystem functioning, as they largely control trophic transfer efficiency to higher trophic levels (Muller-Navarra, *et al.*, 2004). In these locations of the upper canyon, these high concentrations and nutritional quality of sPOM (the latter is defined by the relatively high concentrations of EPA and DHA in sPOM; see Kiriakoulakis *et al.*, 2011) seem to be responsible for the presence of a rich community consisting of cold-water corals and associated organisms (Huvenne *et al.*, 2011; Morris *et al.*, 2013). By contrast, in the deeper and more impoverished parts of the canyon, one finds no cold-water corals. Although the sPOM data in Huvenne *et al.* (2011) were from a small number of locations and the sampling only provided a 'snapshot' (sPOM was collected in early summer 2009 soon after the phytoplankton bloom), the presence of a flourishing *Lophelia pertusa* population is often linked to a supply of relatively fresh OM (Orejas *et al.*, 2009; Wagner *et al.*, 2011; Duineveld *et al.*, 2012; Morris *et al.*, 2013). The exact mechanism between the apparent coincidence *Lophelia* occurrence and the water column characteristics is not clear yet, but it has been suggested that downslope processes like resuspension by internal waves and tides (Ivanov *et al.*, 2004), dense shelf water cascading, sediment gravity flows (Puig *et al.*, 2012) and turbidity currents to greater depths, could result not only in canyon flushing, but also in focused enrichment and deposition of OM to greater depths (Duineveld *et al.*, 2001; Masson *et al.*, 2010). These mechanisms provide favourable environmental conditions (current regime, food input) to sustain the megafauna communities, even when they are outside the optimal depth and density envelopes reported elsewhere in the NE Atlantic.

Recently, Amaro *et al.* (2015) showed with a yearly deployment of sediment traps at the outer deeper (~4000 m depth) central part of the canyon (Whittard Channel) that the occurrence of mass aggregation of megafauna organisms is not necessarily the result of down-canyon transport of OM. Amaro *et al.* (2015) showed, and that the highest flux of fresh OM arriving at the deeper end of the Whittard Canyon is due to local settling of phytodetritus after the spring phytoplankton bloom. In their study gravity-driven episodic events, provided low nutritional quality material.

3.2. Sedimentary organic matter (SOM)

Duineveld *et al.* (2001) showed that the sedimentary organic carbon (SOC) content in the surficial sediments at the middle-lower central channels of the Whittard canyon (2735 to 4375 m water depth) was higher, (0.9–1.1% of dry sediment), than in the surface sediments of the open slope stations of the Goban Spur, (0.4–0.5% of dry sediment), although there was no clear downslope trend. Canyons acting as 'traps' of OM have been observed before in the European Margin (Masson *et al.*, 2010). This was related to the high sedimentation rates in the canyon which promote carbon burial by reducing the oxygen exposure time (OET) of the sediment (Kiriakoulakis *et al.*, 2011). The high SOC levels observed in Duineveld *et al.* (2001) persisted down core to 5 cm in the upper middle section, but deeper the SOC content dropped to levels comparable to the Goban Spur 2–3 cm below the surface. This was attributed to coarser grains sizes of the canyon sediments that increase OET and have a weaker mineral association with OM (Hedges and Keil, 1995). Other investigations (Huvenne *et al.*, 2011; Amaro *et al.*, 2015) showed that surficial sediments in several locations within the Whittard Canyon were practically indistinguishable from open slope values (0.1 – 0.7% SOC of dry sediment). Both studies showed that the highest SOC values were closer to the Whittard Channel (i.e. the deep central section). Clearly the mechanisms for the often mentioned 'OM enrichment' in submarine canyons are not fully understood and perhaps cannot be universally applied. It appears likely that they vary both spatially and temporally in relation to the complex topography and its interaction with the current and tidal regime that could promote deposition or erosion of sediment (Huvenne *et al.*, 2011), the nature of gravity flows (Haughton, 2009), the impact of the resident benthic fauna (Ingels *et al.*, 2011; Amaro *et al.*, 2015) and the supply and lability of OM (Huvenne *et al.*, 2011; Kiriakoulakis *et al.*, 2011).

The lability of sedimentary OM (SOM) from various locations within the Whittard Canyon has been investigated (Duineveld *et al.*, 2001; Huvenne *et al.*, 2011; Ingels *et al.*, 2011; Amaro *et al.*, 2015). The molar C/N ratios of the first 10 cm of sediments mostly show a marine unaltered (i.e. 'fresh') signal (most values 4-8), although there were occasionally higher (up to 20; Duineveld *et al.*, 2001; Ingels *et al.*, 2011). Microbial degradation, benthic bioturbation or episodic deposition of resuspended degraded material with high C/N ratios could all be likely reasons for this observation. In addition there was no consistent trend with depth emphasizing the complexity and the multitude of the transport processes affecting this vast system. Fewer studies have provided a more detailed insight on the bioavailability of SOM, mainly by investigating phytopigments, nucleic and fatty acids in selected locations. Duineveld *et al.* (2001) showed that concentrations of phytopigments and nucleic acids decreased both down slope and down core within the canyon, suggesting a lowering of OM bioavailability both in fine (vertical) and larger (distance from shelf) scales. Ingels *et al.* (2011) supported the former observation by showing that small scale (vertical) heterogeneity in SOM quality (expressed mainly as relative contributions of phytopigments to Carbon) within the same core can explain much of the variation of the meiofaunal communities of the canyon. The importance of SOM (nutritional) quality to benthic communities has also been highlighted by Huvenne *et al.* (2011), and Amaro *et al.* (2015) who found appreciable concentrations of essential fatty acids (EPA and DHA) in the surficial sediments from several areas of the central upper and middle parts of the canyon. These seem to be associated with the presence of CWCs in the same areas. Similarly Amaro *et al.* (2015) showed that 'fresh' OM (using phytopigments as proxies) in sediments from the Whittard Channel was associated with abundant elpidiid holothurians. Latter organisms have been frequently found associated with favourable quality and quantity of sedimentary OM (De Wilde *et al.*, 1998; Amaro, *et al.*, 2010; Billett *et al.*, 2010; De Leo *et al.*, 2010). The same authors suggested that the SOM origin was related to overlying phytoplankton blooms rather than gravity driven processes through the canyon. When these were detected (using sediment traps) they resulted in accumulation of low quality degraded material.

4. Conclusion

This overview represents the first attempt to reveal the fuller picture of the flow of the OM transfer through Whittard Canyon and its effects on the megafauna communities. The Whittard Canyon seems to play a role in transfer of shelf production (and terrestrial carbon) to the deep sea. The OM quality seems to depend on the overlying production of the water masses and the distribution of the fresh OM seems to be coupled with processes in the canyon such as the gravity flow events. However, down the canyon and specifically on the Whittard channel, the fresh OM found in the area is decoupled from such processes and most of the OM supply is more likely linked to local phytodetritus deposition, concentrated within the topographic depression formed by the Whittard Channel after redistribution by bottom currents. The occurence of abundant megafauna communities both in the upper canyon and channel is linked to OM quality and quantity. However, the data analysed here are only a snapshot of the conditions within the Whittard Canyon. There is a need to get more data on mega-macro-meiofauna abundances in Whittard Canyon in relation to OM (quality, quantity) thru a multi-year study to understand the processes behind these patterns. In submarine canyons susceptible to being affected by dense shelf-water cascading events, simultaneous measurements of water temperature and salinity should be made to compute water density. Observations in submarine canyons should be combined with external forcing conditions (e.g., winds, surface waves, and river discharges) to correctly discern the mechanisms involved in shelf-to-canyon sediment delivery.

Acknowledgements

This study was partially supported Marie Curie Actions through the project CEFMED (project number 327488).

---

* this chapter is to be cited as:

Amaro T., Kiriakoulakis K. 2015. Organic matter transport and deposition in the Whittard Canyon and its possible effects on benthic megafauna. pp. 97 - 101 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.

Submarine canyons of the Black Sea basin with a focus on the Danube Canyon

Irina Popescu[1], Nicolae Panin[2], Dan Jipa[2], Gilles Lericolais[3] and Gabriel Ion[2]

[1] *National Institute of Marine Geology and Geo-ecology Romania – presently European Parliament*
[2] *National Institute of Marine Geology and Geo-ecology Romania;*
[3] *Ifremer, France*

Abstract

The first part of the paper presents an overview of the Black Sea canyons which are evident in the present-day morphology of the marine basin. Two types of canyons are revealed – the active and the passive canyons. The study then concentrates on the analysis of the Danube Canyon. The canyon morphology is reviewed, in correlation with the Upper Quaternary paleo-Danube channels and the structure of the Danube Deep Sea Fan. Erosive flow along the canyon axis producing bottom down-cutting and instability of the walls is regarded as the process controlling the morphological evolution of the Danube Canyon. The lowstand-time morphology of the shelf is reconstructed, based on the filled-up paleo-channels and the wave-cut terrace extension. The buried channels clusters suggest two main directions of the paleo-Danube drainage systems, partly discharging in the Danube Canyon. The high paleo-Danube sedimentary influx appears to represent the major control on the canyon development. The age constraints for the canyon initiation are currently non-existent. It is conceivable that the youngest phase of evolution of the Danube Canyon corresponds to the last Black Sea lowstand.

1. Introduction

1.1 Objectives, methodology, study area

For the sediments discharged by rivers in marine basins, the canyons are the most important way to reach their final destination, the deep marine bottom. Due to the diversity of its surrounding terrestrial relief (Fig. 1), the Black Sea accommodates many canyons with multiple aspects. Ignored for a long time by scientists, the Black Sea canyons slowly begin to represent attractive themes of study. Beneficiary of several international research projects, the Danube Canyon is now at a relatively high level of knowledge, representing a reference point for other studies of this kind from the Black Sea area.

The present paper stands for a review of the information regarding the Black Sea canyons. Sparse literature data are the base for the Black Sea canyons overview. The focus of this study is on the Danube Canyon, covering a study area at the edge of the northwestern Black Sea shelf. The head of the Danube Canyon is located 130 km east of the town of Constanţa (Romania). The canyon is extended southeastward by the Danube Channel, through the Danube Deep Sea Fan (Fig. 1). Complex geological and geophysical investigations (swath bathymetry in the canyon area combined with sub-bottom profiling and different types of seismic profilings) were carried out in this area in the framework of national, French-Romanian and German-Romanian common projects (Winguth *et al.*, 1997, 2000; Wong *et al.*, 1994, 1997, 2002; Panin 1996, 2009; Popescu, 2002; Popescu and Lericolais, 2003; Popescu *et al.*, 2004, Lericolais, 2007), and these data are analysed.

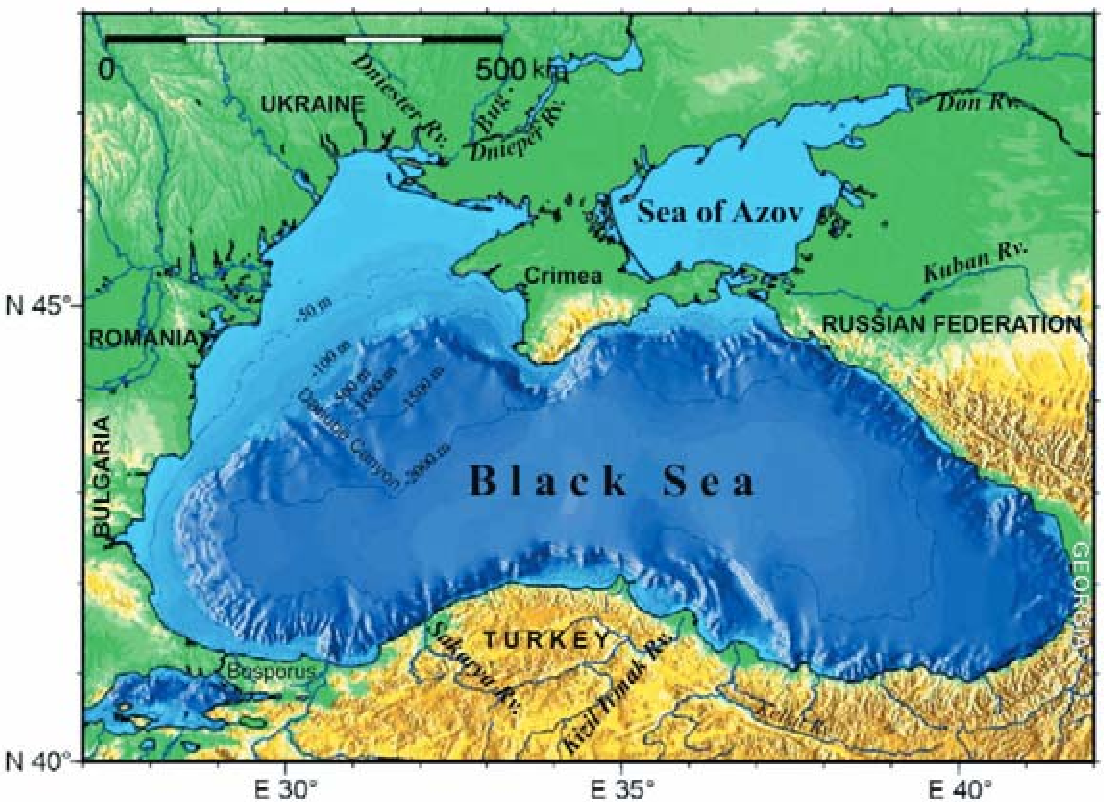


Figure 1. Black Sea morphology. Detailed view of the northwestern Black Sea area. Earth satellite image.

1.2. Black Sea general features

The Black Sea is located almost at the boundary between Europe and Asia. The southeastern and northeastern Black Sea is constrained by the Pontic and Caucasus Mountains. The Crimean Mountainous Peninsula borders the sea basin to the north. Low relief terrain (lowstanding loess plateaux, the Danube delta and the Dobrogean geological units) surrounds the northwestern and western Black Sea. The south-western section of the sea is again mountainous – the Balkans Mountains flank the coastal zone.

Hydrology and hydrochemistry. The almost total isolation is one of Black Sea special characteristics. The Black Sea is connected to the Mediterranean Sea through the Bosporus-Dardanelles narrow system of straits (called also Turkish Straits). In this geographic isolation condition, due to the high fresh water runoff, the Black Sea salinity is quite low for a marine body (17 to 22 ‰).

The Black Sea temperature and salinity stratification restricts the vertical water mixing, and consequently the oxygen from atmosphere does not reach the deep water, which became anoxic. The decaying organic matter accumulated in time led to the present day hydrogen sulphide saturation of the deep, anoxic Black Sea water. The upper layer of oxic marine water (about 150 – 200 m thick) practically supports the entire biological life in the Black Sea ecosystem.

Coastline. The 4870 km long Black Sea coastline (Stanchev *et al.*, 2011) is shared by six states, Turkey, Georgia, Russian Federation, Ukraine, Romania and Bulgaria.

Three main Black Sea morphodynamic types of coasts are distinguished by Panin (2005): (1) low, accumulative coasts, in the areas of the main river mouth zones, mainly with sandy complex barrier beaches; (2) erosive coasts within which active cliffs in loess and loess-like deposits lowstanding plateaux and plains, sometimes with very narrow beaches in front of the cliffs; (3) mountainous coasts, with cliffs, marine terraces, landslides, with sandy or gravely beaches.

1.3 Physiography

The Black Sea shelf represents about 30% of the sea area (Ross *et al.*, 1974; Panin, Jipa, 1998). The largest shelf development is in the northwestern part of the Black Sea, between the Crimean peninsula and the Danube Delta, where the shelf can be more than 190 km wide (Fig. 2). In contrast the shelf width from the southern and eastern Black Sea is less than 20 km (Ross *et al.*, 1974). The shelf is mostly shallower than 100 m, but in the northwestern area the shelf break reaches -140 m to -170 m in water depth (Popescu, 2002).

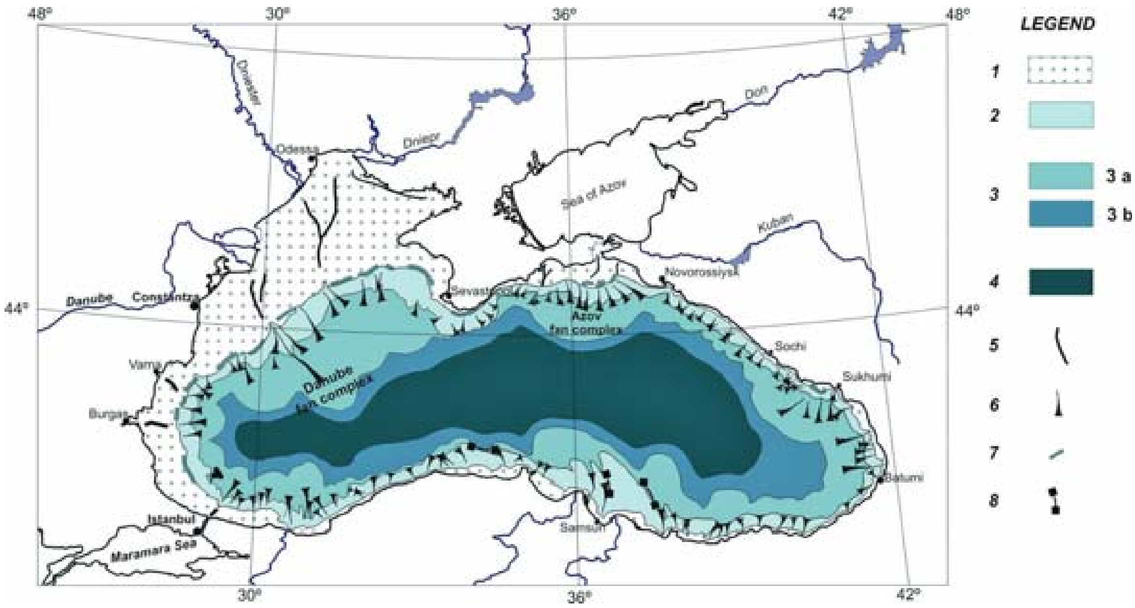


Figure 2. Geomorphologic zoning of the Black Sea (after Ross *et al.*, 1974, Panin, E and G. Ion, 1997). Legend: 1, continentals shelf; 2, continental slope; 3, basin apron: 3a - deep sea fan complexes; 3b - lower apron; 4, deep sea (abyssal) plain; 5, paleo-channels on the continental shelf filled up 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.

Along the high relief southern and north-eastern Black Sea coasts, the continental slope is steeper and crossed by numerous canyons. The slope area associated with the wide shelf from the northwestern Black Sea is smoother and its gradient is gentler.

In the deep Black Sea area, Ross *et al.* (1974) separated the basin apron and the abyssal plain physiographic units. Distinct features of the basin apron are deep sea fans of large tributaries and mainly of the Danube River. The Euxine Abyssal Plain, from the almost plane area in the central part of the Black Sea, represents only about 12% of the sea surface (Ross *et al.*, 1974).

The differences in the continental shelf width of western and north-western Black Sea, compared to the eastern and southern sections of the sea, control the dynamics of canyons located in the respective regions: in the mountainous eastern and southern coastal zones where the shelf is narrow the canyons are active even during the highstands and capture entirely or partially the sediment load brought by rivers into the sea, while in the area of very wide shelf the canyons are active only during lowstands.

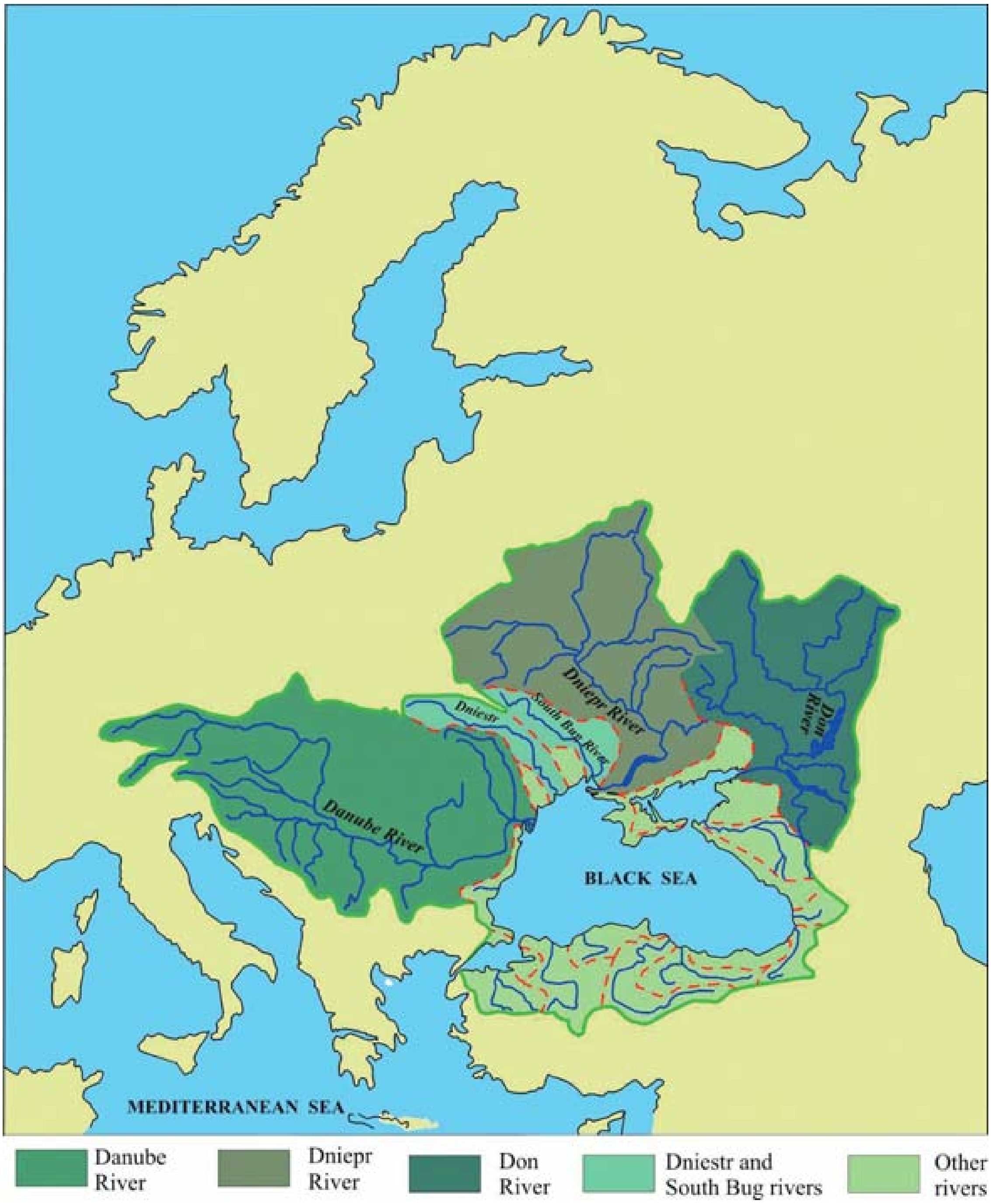


Figure 3. The Black Sea drainage basin (from Popescu, 2002).

1.4 Sediment input

The Black Sea drainage basin is very large, summing more than 2 million sq.km, and the water is collected from about one third of the Europe territory (Fig. 3). The largest rivers, with the greatest catchment basins and the larger water and sediment discharge are located in the northwestern

Black Sea. The Danube River has a mean water discharge of about 200 $km^3.yr^{-1}$ and the Ukrainian rivers Dnieper, Southern Bug and Dniester contribute with about 65 $km^3.yr^{-1}$.

The Danube River is the predominant sediment contributor. Its influence extends up to the Bosporus region, and down deep in the Black Sea basin. Dniester, Dnieper and Southern Bug rivers are presently discharging their sedimentary load into lagoons separated by beach barriers from the sea. During the lowstands all these rivers supplied sediments directly to the deep Black Sea.

After the Iron Gates I and II dams were built in 1970 and 1983 respectively, the Danube sediment discharge diminished by almost 40-45 % and the sediment load introduced by the Danube River into the Black Sea is not larger than 30-40 million t/yr. (Panin and Jipa, 1998, 2002). Out of this sediment stock the littoral zone in front of the Danube Delta receives only 10-12 % representing sandy material.

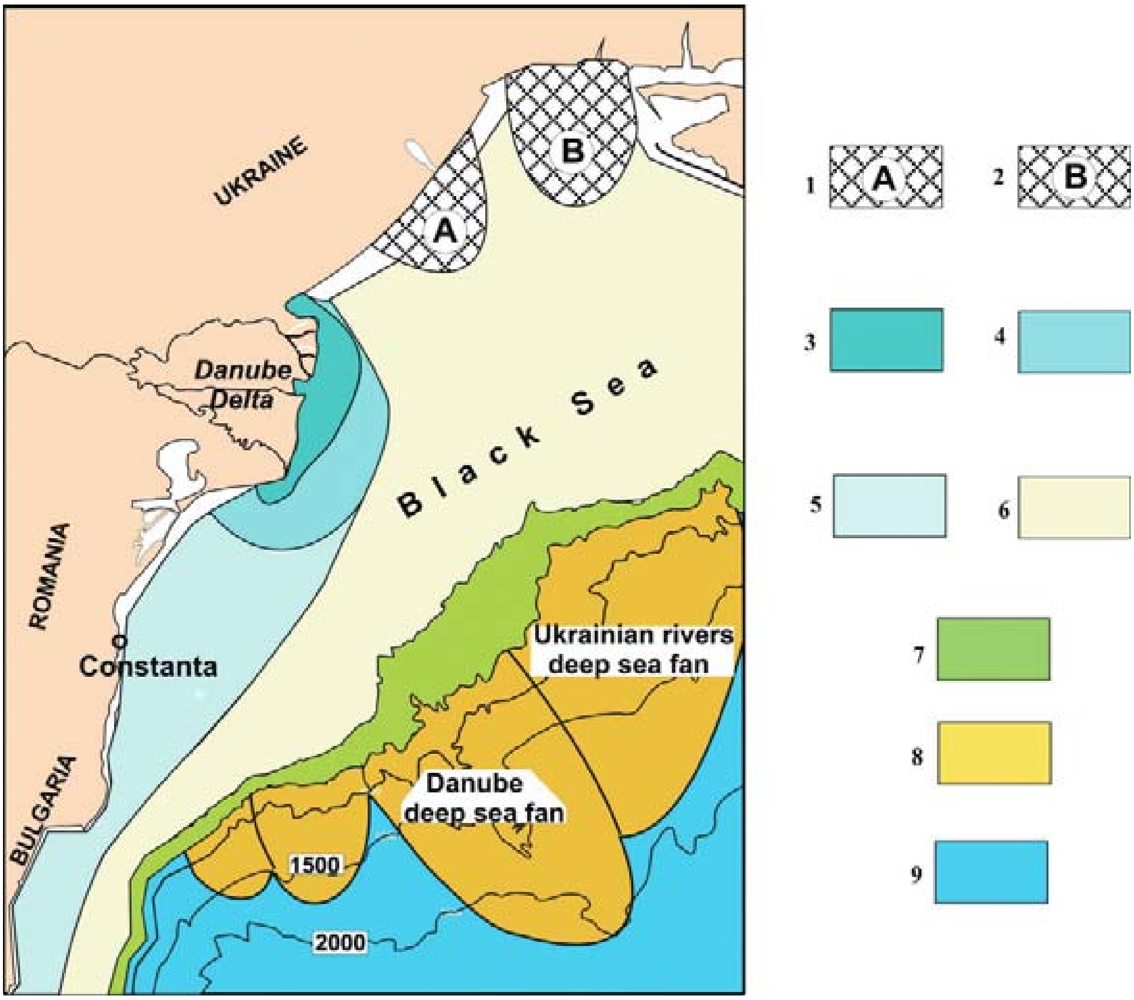


Figure 4. Main sedimentary environments in the north-western Black Sea (after Panin and Jipa, 1998, 2002). Legend: 1-2, Areas under the influence of Ukrainian rivers (A, Dniester; B, Dnieper) sediment discharge; 3, Danube Delta front area; 4, Danube prodelta area; 5-6, Western Black Sea continental shelf areas (5, area under the influence of the Danube-borne sediment drift; 6, sediment starved area); 7, Shelf break and the uppermost continental slope zone; 8, deep-sea fans area; 9, deep sea floor area.

1.5 Black Sea sediments distribution

Sandy sediments dominate in the coastline area. On the shelf besides shelly sediments, a variety of silty and muddy deposits are well developed. The distribution of the main sedimentary environments on the north-western Black Sea continental shelf is illustrated in Fig.4. The deepwater sediments are very fine grained, consisting of Coccolith muds with various carbonate content. Silty and sandy sediments were deposited by turbidity currents on the basin slope and in deeper areas (Shimkus and Trimonis, 1974).

1.6 Past Black Sea level and environmental changes in the Upper Quaternary - Holocene

Along the Black Sea geologic history large-scale sea level changes and consequently drastic reshaping of land morphology, strong erosions and large accumulation of sediments in the deep part of the sea have led to significant modifications of the environmental settings. The Quaternary was especially characterised by very spectacular changes, driven by global glaciation and deglaciation episodes.

During these changes the Black Sea level behaviour was influenced by the restricted connection with the Mediterranean Sea via the Bosporus – Dardanelles straits. When the general sea level lowered bellow the Bosporus sill, the further variations of the Black Sea level followed specific regional conditions, without being necessarily coupled to the Ocean level changes.

One of the main consequences of the lowstands was the interruption of the inflow of Mediterranean water into the Black Sea, which became a brackish or almost freshwater giant lake.

The main glacial periods of the Quaternary in Europe (Danube, Günz, Mindel, Riss and Würm) corresponded to regressive phases of the Black Sea as well, with lowstands down to –100 and even -120 m. As mentioned above, the regressions represent phases of isolation of the Black Sea from the Mediterranean Sea and the World Ocean. Only the connection with the Caspian Sea could sometimes continue through Manytch valley.

Correspondingly, during regressions, under brackish/fresh water conditions, the particularities of fauna assemblages had a pronounced Caspian character. On the contrary, during the interglacials, the water level rose to levels close to the present level; the Black Sea was reconnected to the Mediterranean Sea, and the environmental conditions as well as the fauna characteristics underwent marine Mediterranean influences.

We shall discuss mainly the upper part of the Pleistocene when the lowstands influenced the present-day Danube canyon morphology and evolution.

During the warm Riss-Würmian (Mikulinian) interglacial that corresponds to the Karangatian phase of the Black Sea (since 125 ka BP to ~ 65 ka BP), the water level exceeded the present-day level by few metres (8 to 12 m). The saline Mediterranean water penetrated through the Bosporus, and the Black Sea became saline (up to 30 even 37 ‰), with a steno- and euri-haline marine Mediterranean type fauna (Nevesskaya, 1970). The sea covered the lowlands in the coastal zone, including also the Danube river mouth zone (a large gulf was formed at that time).

The last Upper Würmian glaciation (Late Valdai, Ostashkovian) corresponds to the Neoeuxinian phase of the Black Sea. This is a very low-stand phase, down to -110 ÷ -120 m. The shoreline moved far away from the present-day position, especially in the northwestern part of the Black Sea, and large areas of the continental shelf were exposed. At depths between -100 m and -80 m, a drowned paleo-shoreline represented by wave cut terraces and fields of dune–like structures occurs (Popescu *et al.*, 2004; Ryan, 2007; Lericolais *et al.*, 2007). The hydrographic network, especially the large rivers as Paleo-Danube and Paleo-Dnieper, incised up to 90 m the exposed areas. The Neoeuxinian basin during the glacial maximum (~19 ÷ ~16 ka BP) was completely isolated from the Mediterranean Sea, and, correspondingly, the water became brackish to fresh (3÷7 ‰ and even less), well oxygenated, without H_2S contamination. The fauna was brackish to fresh water type with Caspian influence.

At about 16 ÷ 15 ka BP the postglacial warming and the ice caps melting started. As the supply of melting water from the glaciers through the Dnieper and the Dniester rivers, as well as the Danube River, to the Black Sea was very direct and important, the Neoeuxinian sea-level rose very quickly, reaching and overpassing at ~ 12 ka BP the Bosporus sill. Some researchers believe that in this phase a large fresh-water outflow through the Bosporus-Dardanelles straits towards the Mediterranean (Aegean) Sea occurred. Kvasov (1975) calculated that the fresh water outflow discharge was about 190 km^3/year.

At the beginning of the Holocene, some 9-7.5 ka BP, when the Mediterranean and the Black Seas reached the same level (close to the present day one), a two-way water exchange was established, and the process of transformation of the Black Sea in an anoxic brackish sea started. During the last 3 ka BP, a number of smaller oscillations of the water level took place ("Phanagorian regression", "Nymphaean" transgression, a lowering of 1÷2 m in the Xth century AD, with a slow rising continuing up-today).

The hypothesis formulated by Ryan *et al.* (1997) considers that during the Younger Dryas cooling (~11 ka BP until 9 ka BP), under more arid and windy climate, the Black Sea experienced a new lowering of the level (down to more than -100 m). At the same time, the Mediterranean Sea continued to rise, reaching by 7.5 ka BP the height of the Bosporus sill, and generating a massive inflow of salt water into the Black Sea basin.

More recent interpretations propose refined scenarios of reconnection of the Black Sea with the Mediterranean. Data seem to indicate a rapid transition from a fresh to brackish lake to the modern Black Sea around 9400 years ago (Ryan *et al.*, 2003; Major *et al.*, 2006; Hiscott *et al.*, 2007; Bahr *et al.*, 2008).

It seems that a highstand at about -20–30 m was reached during the deglacial to the earliest Holocene, but the timing and the temporal extent of this event is still under discussion (Ryan *et al.*, 2003; Hiscott *et al.*, 2007; Lericolais *et al.*, 2007a). The present-day Danube canyon is related to the last lowstands of the Black Sea – the Neoeuxinian one and, possibly, those of Younger Dryas.

2. Black Sea canyons – background

Information regarding Black Sea canyons is not very abundant. Aspects of the Black Sea canyons will be found in Algan *et al.* (2002), Wong *et al.*, (1994 and 1997), Lericolais *et al.*(2002), Dimitrov and Solakov (2002), Popescu and Lericolais (2003). Popescu *et al.* (2004), Dondurur and Çifçi (2007), Pasynkova (2013) and Gulin (2013).

Significant knowledge on canyon heads came through the investigation of the coastal zone morphodynamics carried out by Georgian scientists (Bilashvili, 2004; Papashvili *et al.*, 2010) while cruises focused on deep-water cold seeps or deep sea fans provided important data on the lower reaches of some Caucasian or west Crimean submarine canyons (Lüdman *et al.*, 2004; Akhmetzhanov *et al.*, 2005; Naudts *et al.*, 2006; Klaucke *et al.*, 2006; Bohrmann and Pape, 2007; Wagner-Friedrichs, 2007; Sipahioglu, 2013).

2.1 Black Sea canyons and the coastline morphodynamics

Black Sea canyons characteristics depend on the relief energy of the coasts they are associated with. From this viewpoint the Black Sea offers two different environments (see Fig. 1).

The southern and eastern Black Sea coastline is mountainous. The relief behind this coast is very high, with summits of almost 4000 m (3937m - Kaçkar Dağı in the North Anatolian Mountains) or close to 6000 m (5642 m - Mount Elburs in the Greater Caucasus Mountains). In the southern Crimean Peninsula the relief is also elevated, but the altitude is in the 600-1,545 m range.

From the Crimean Peninsula to the north of the Bosporous Strait the Black Sea coast shows a low relief, reaching a hilly morphology only southward of Varna (the easternmost extension of the Balkans) and northward of Constanţa (Northern Dobrogea Plateau). This is a low, accumulative coast (Panin, 2005).

In the Black Sea basin the shelf extension is well correlated with the shoreline morphodynamics, and this also influences canyons development. More frequent submarine canyons occur in the southern and eastern Black Sea area with mountainous shoreline, very narrow shelf (Fig. 1) and coarse-grained sediments. In areas with low-relief shoreline, the shelf is wide and have fine-grained (sandy and silty) sediments (like in the northwestern Black Sea area) and the submarine canyons are scarcer and less closely spaced.

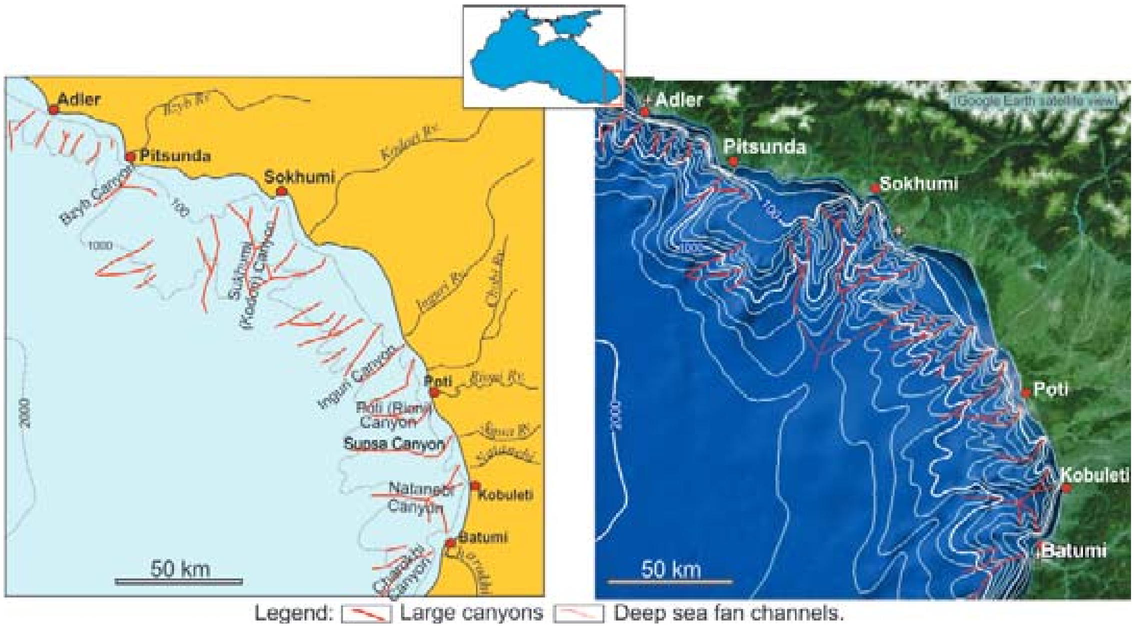


Figure 5. Major submarine canyons from the Caucasian, eastern Black Sea. Google Earth satellite view used as background image. Bathymetry in meters.

2.2 Submarine canyons in the eastern, Caucasian Black Sea area

The submarine canyons located close to the Caucasian coast are the most renowned in the Black Sea area. In this area a close relationship appears to exist between the canyon and the rivers. The major canyons of this area (Bzyb, Kodori, Inguri, Rioni, Supsa, and Chorokhi/Çoruh) are all associated with rivers (Jaoshvili, 2002).

The Caucasian coast is associated with very narrow shelf areas. In the Batumi-Kobuleti, SE of Sokhumi and Adler-Pitsunda zones (Fig.5) the shelf is less than 5 km wide. In these areas the canyon's heads incise the narrow shelf, and are located at close vicinity of the rivers mouth. The Chorokhi canyon head appears at 70-140 m from the Chorokhi (Çoruh) river mouth, at 7-8 m water depth (Bilashvili, 2004). Before harbor and river management works were carried out, the Poti submarine canyon head was surveyed at the 10 m isobath and at about 600 meters from the shoreline and from one of the Rioni river mouths (Papashvili *et al.*, 2010). The head of the southern branch of the Natanebi Canyon occurs at the Batumi harbor entrance, at about 10 m water depth (Bilashvili, 2007).

The shelf is wider and the continental slope gentler slope in the Pitsunda – Sokhumi marine area and between Kodori and Inguri canyons. This is why the canyons from these areas occur 25-35 km offshore.

Seismic sections (Akhmetzhanov *et al.*, 2007) point out the concave-upward profile in the canyons lower reach parts, at water depth of 1400-1600 m. On the bottom of the Sokhumi and Natanebi canyons there are gravels with large current ripples and also very large scours.

The seismic investigations carried out by Sipahioglu (2013) revealed the presence of several older, buried channels in the canyons sedimentary structure from the marine area westward of the Chorokhi (Çoruh) river mouth. The arrangement of these erosion surfaces reveals limited lateral migration of the submarine valley and in other cases the longtime persistence of the canyon.

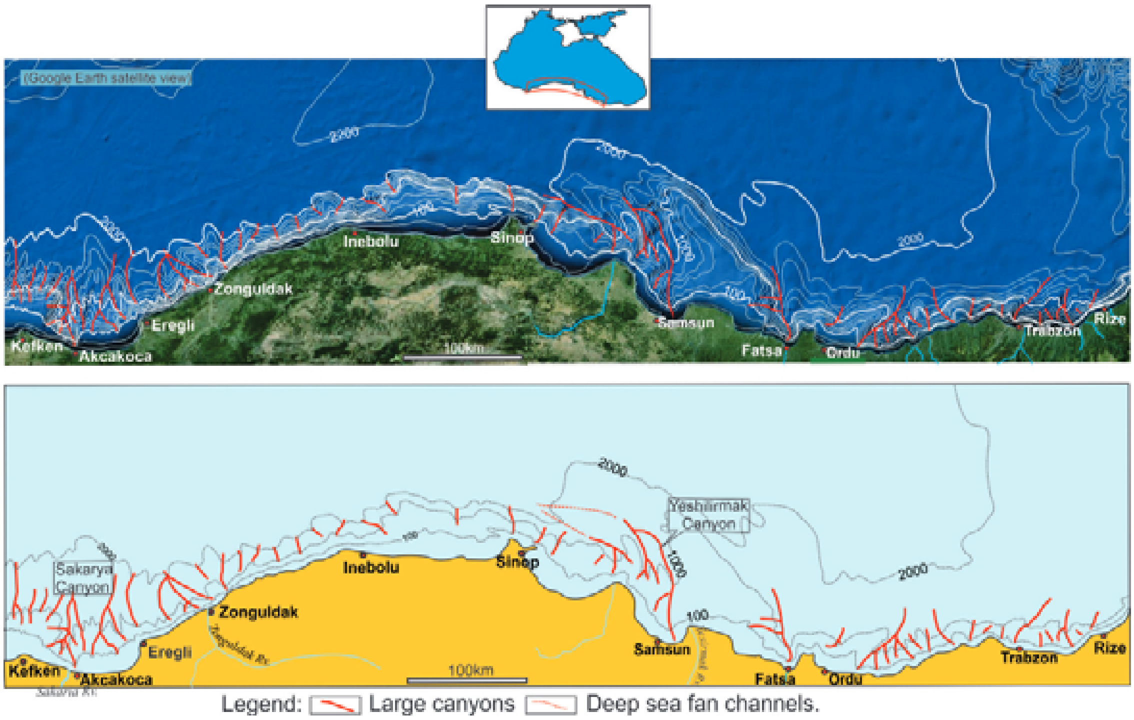


Figure 6. Large canyons from the southern Black Sea, the Anatolian area. Google Earth satellite view used as the background image. Bathymetry in meters.

2.3 Submarine canyons of the Anatolian, southern Black Sea area

The Anatolian zone is the largest Black Sea mountainous coast, with a 900 km east-west extension (Fig. 6). Steep slope and shelf areas (Eregli-Inabolu and Fatsa-Rize) of 2-4 km width alternates with less extensive areas of larger shelf (7-10 km width in Fatsa-Sinop and Eregli-Kefken marine zones) and gentler slope, associated with deep sea fan build up. The main canyons (Sakarya and Yeshilirmak) appear in the milder slope areas. They have a higher dendritic trend, showing a system with a main channel thalweg and several limbs.

On the large scale bathymetric maps, some of the Anatolian canyons appear to cross or reach the 100 m bathymetric curve and could be considered as shelf-incising. This is the case of the Sakarya Canyon. As Algan *et al.* (2002) specified the Sakarya Canyon displays two heads, occuring at about -50m and respectively -10m water depth.

Mapping the continental slope in the area of the Yeshilirmak River mouth Dondurur and Çifçi (2007) have been able to accurately trace the canyons axes. In this way they revealed a very dense, dendritic system of canyons. The canyons heads are 3 to 9 km away from the shelf break, at 500 to 800 m water depth, which is a good example of slope-confined canyons.

2.4 Black Sea canyons of the Crimean area

The submarine canyons from the Crimean area occur within two physiographic zones: the gentle slope of the Don-Kuban deep sea fan and the steep slope of the Sevastopol-Yalta (Crimean escarpment) and Anapa-Gelendzik areas (Fig. 7). The Don-Kuban (Kumani) Canyon, the best known from the area, is well indenting the shelf south of the Kerch Strait.

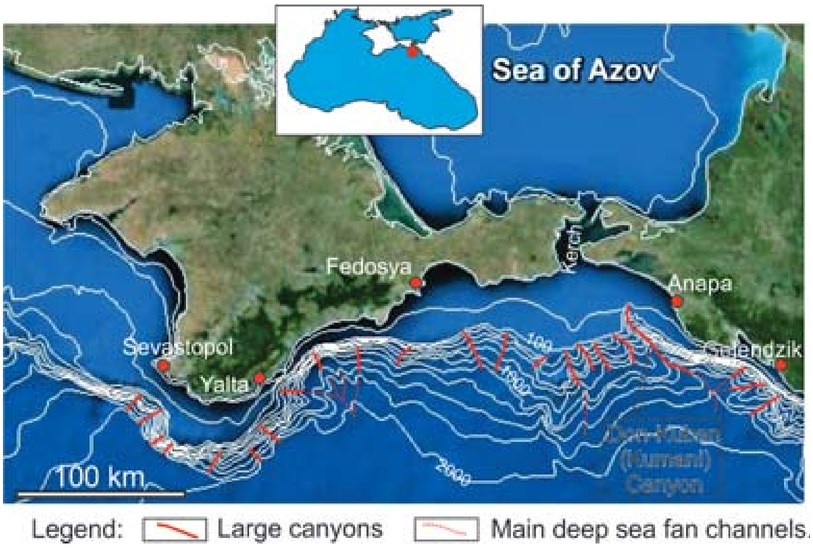


Figure 7. Large canyons from the northern Black Sea basin, the Crimean area. Satellite picture from Google Earth. Bathymetry in meters.

2.5 Black Sea canyons of the Bosporous area

Completing the previous data by Di Iorio *et al.* (1999), Okay *et al.* (2011) mapped the eastern Bosporous outlet area and identified a shallow marine fan and a canyon system. The canyons appear as a bunch of submarine valleys oriented transversally to the coast alignment (Fig. 8). The main Bosporous canyons are 50-55 km long. Within this system at least 12 canyons are distributed in an about 115 km wide area, northeast of the Bosporous Strait. They are quite closely spaced, with a 7-8 km distance between adjacent canyons. The dendritic aspect of the Bosporous canyons is minimal, the main canyons showing no more than one limb.

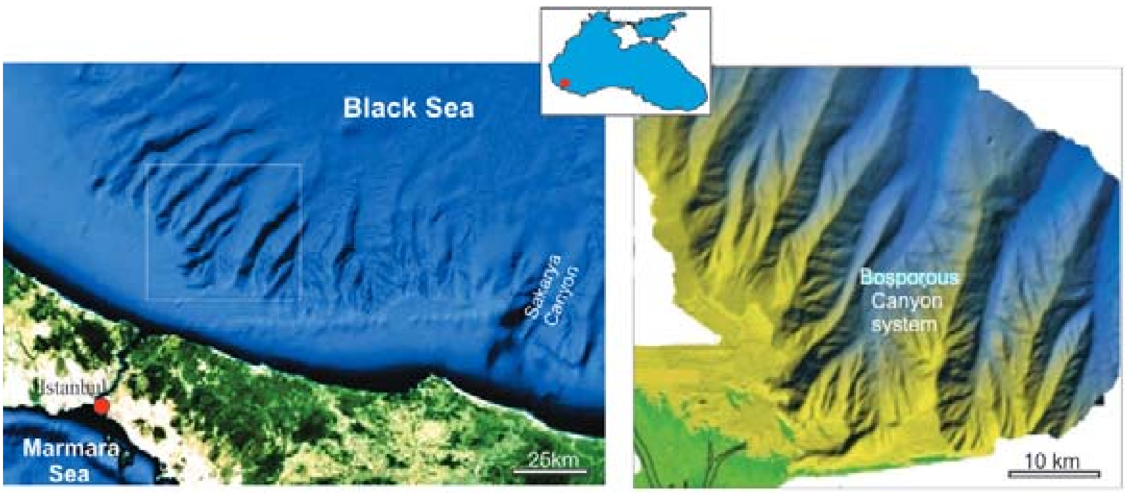


Figure 8. Bosporous submarine canyon system. Left-side image (from Google Earth) shows the general distribution of the Bosporous canyons. Detail of the central canyon system (modified from Okay *et al.,* 2011) in the right-side image.

2.6 Submarine canyons of the western Black Sea basin

Unlike all other Black Sea canyons, the canyons in the western part of the basin occur far away from the coastline, at the edge of a wide shelf (Fig. 9). Presently they have no connection with rivers, and are not functional.

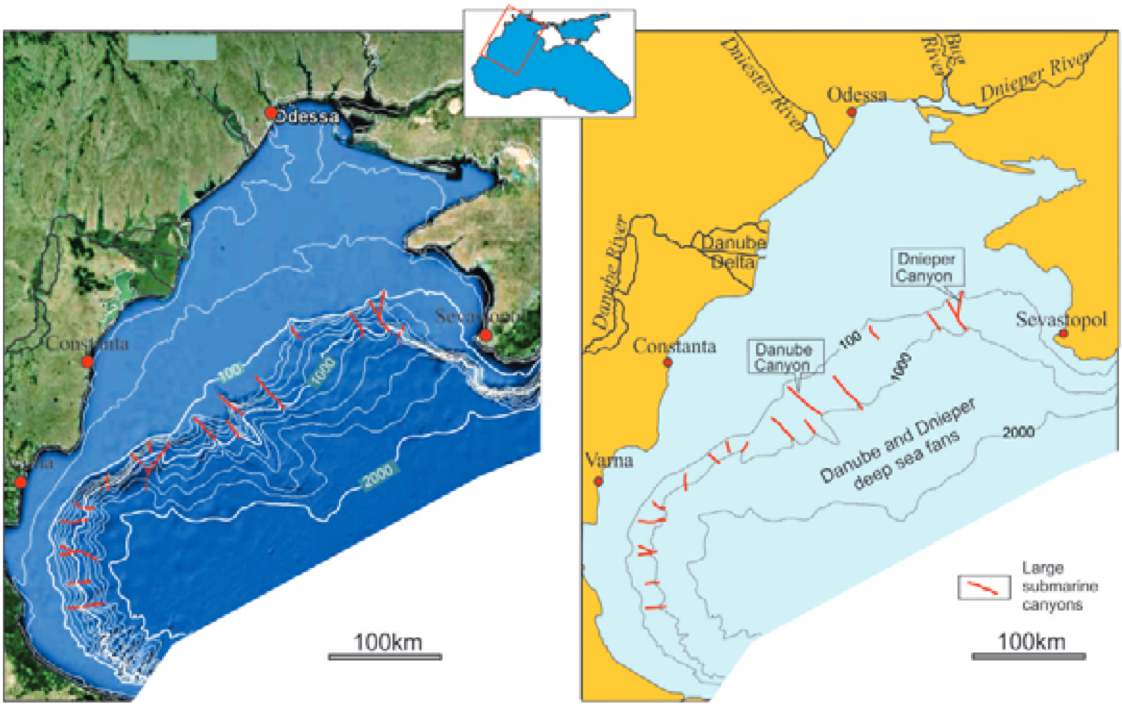


Figure 9. Large submarine canyons from the western and northwestern Black Sea basin. Satellite picture from Google Earth. Bathymetry in meters.

The most important canyons from the western and northwestern Black Sea basin are the Danube Canyon and the Dnieper Canyon (Fig. 9). They are both shelf-indented, but the smaller canyons close by are not incising the shelf. The larger development of the Danube and Dnieper canyons was facilitated by the longer and milder slope connected with the extensive Danube and Dnieper deep sea fans.

The submarine canyons distributed on the edge of the Bulgarian shelf, where the continental slope is steeper, are shorter and seem to be slope-enclosed.

3. The Danube river canyon – a case study

3.1 Morphology

The Danube Canyon (also called the Viteaz Canyon) is part of a 60 km long submarine trough with a NW to SE course (Fig.10).

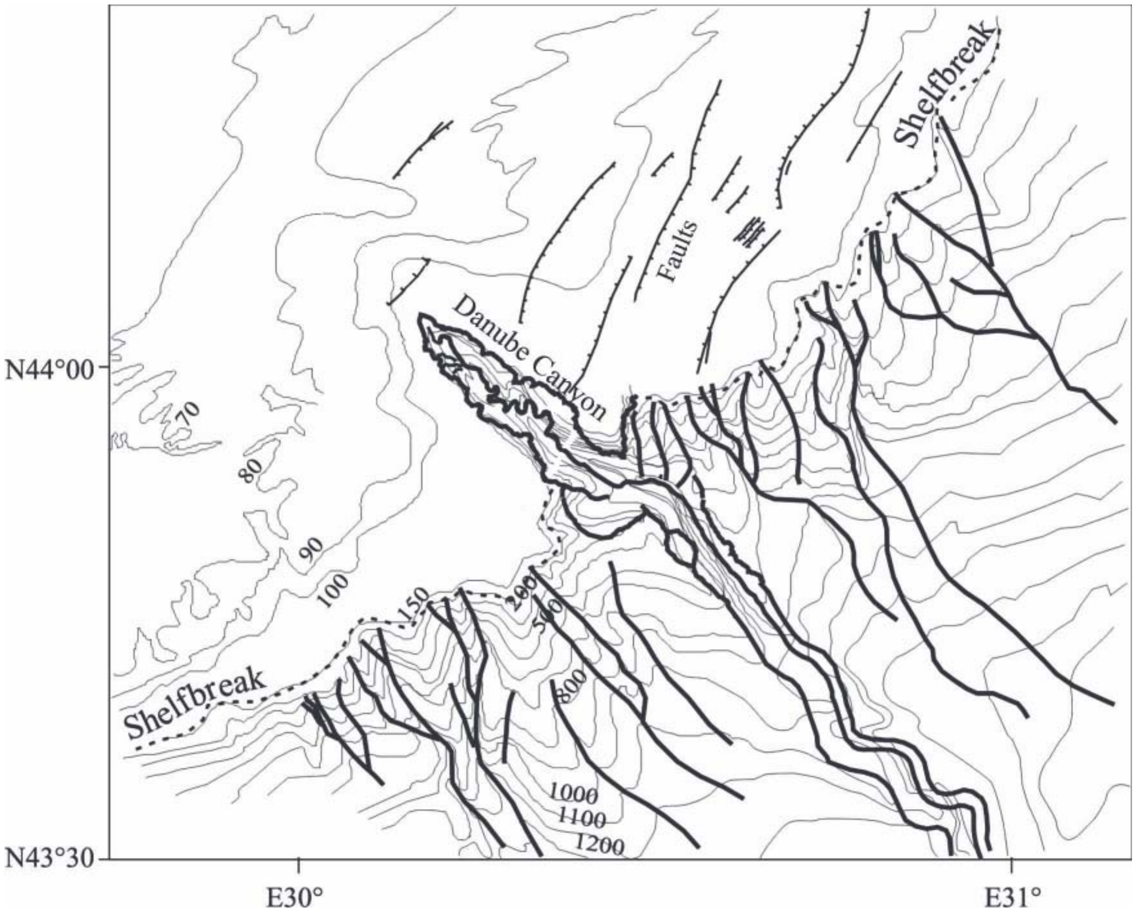


Figure 10. Morphology of the north-western Black Sea margin (after Popescu *et al.,* 2004). The Danube canyon is deeply incised into the shelf.

The 26 km shelf-indented segment of the trough, northwestward from the shelfbreak, is the Danube Canyon. At the shelfbreak level the canyon is about 6 km wide, and landward is getting narrower (Fig. 11). The canyon flanks are steep, with up to 30° declivity. They are part of an older erosional surface, infilled by sediments with a chaotic seismic facies, overlain by well bedded sediments (Fig. 12). The modern thalweg, 400 to 600 m wide and up to 400 m deep, is cut into these stratified sediments. The canyon shows significant longitudinal changes in morphology, direction and gradient. In the southeastern part of the canyon (segments C, D and E in Fig. 11), close to the shelf-break, there is a single entrenched axial thalweg, downstream progressively becoming more stable, straighter and deeper.

Strong meandering of the thalweg line, including meanders, is visible in the sector C of the canyon (Fig. 11). The canyon shows significant longitudinal changes in morphology, direction and gradient. In the southeastern part of the canyon (segments C, D and E in Fig. 11), close to the shelf-break, there is a single entrenched axial thalweg, downstream becoming progressively more stable, straighter and deeper. Strong meandering of the thalweg line, including abandoned meanders, is visible in the sector C of the canyon (Fig. 11).

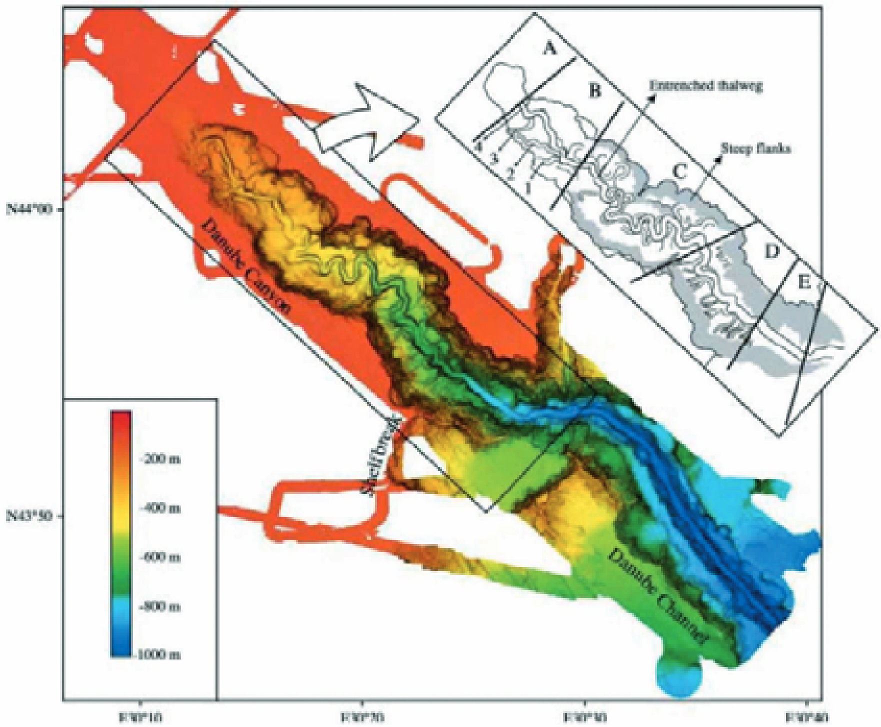


Figure 11. Bathymetric 3D map of the Danube Canyon (EM 1000 multibeam data) (from Popescu *et al.,* 2004). The inset box shows a schematic representation of the canyon morphology, and the segments A to E separated along the canyon. Distinct paths of the thalweg in segment B are numbered 1 to 4. Shaded areas mark the steep canyon flanks.

Close to the landward end of the canyon, the segment B (Fig. 11) is a trough with several converging small channels (1 to 4 in Fig. 11) and with gentler walls. At the landward extremity (segment A in Fig. 11) the canyon bed is concave, with no thalweg line and its walls are even less inclined.

Downstream of the shelfbreak the submarine valley becomes a channel, with smooth, concave-up profile. A knickpoint marks the boundary between the canyon and the channel.

The canyon longitudinal profile points to the strong entrenching of the valley, from less than 40m in segment A to about 230m in segment B, approximately 400 m corresponding to the segment C and 600 m close to the shelf break (segments D and E) (Fig. 13). Along with the continuous axial entrenchment, the canyon walls become steeper and steeper and wider and wider downstream (from 5° to 20° – 30° steep and from 2 km to 6 km wide).

3.2 Genesis and evolution

The transversal seismic reflection profiles reveal the presence of an erosion surface at about 240 m under the present-day thalweg (Fig. 12). This surface reflects the erosion process which initiated the first submarine valley stage. This morphologic inherited feature was subsequently developed by the erosional and depositional activities of the Danube Canyon. Thalweg downcutting caused instability of the flanks, probably triggering headward erosion of the canyon as in the apparently immature segment B (Fig. 11). Erosion in the axial thalweg also resulted in failures enlarging the major valley in the mature segments D and E (Fig. 11), directly (on the northern flank) or through a system of lateral gullies (on the southern flank). Segment C is a zone affected by erosion as well: perched terraces were created by failures inside the major valley, while abandoned meanders nearby the canyon walls determined the instability and widening of the canyon. The sediments with two different seismic facies are the result of the repeated stages of partial sedimentary infilling of the canyon trough. As revealed by the study of other submarine canyons (Shepard, 1981), the Danube Canyon evolved through a succession of erosion and deposition events.

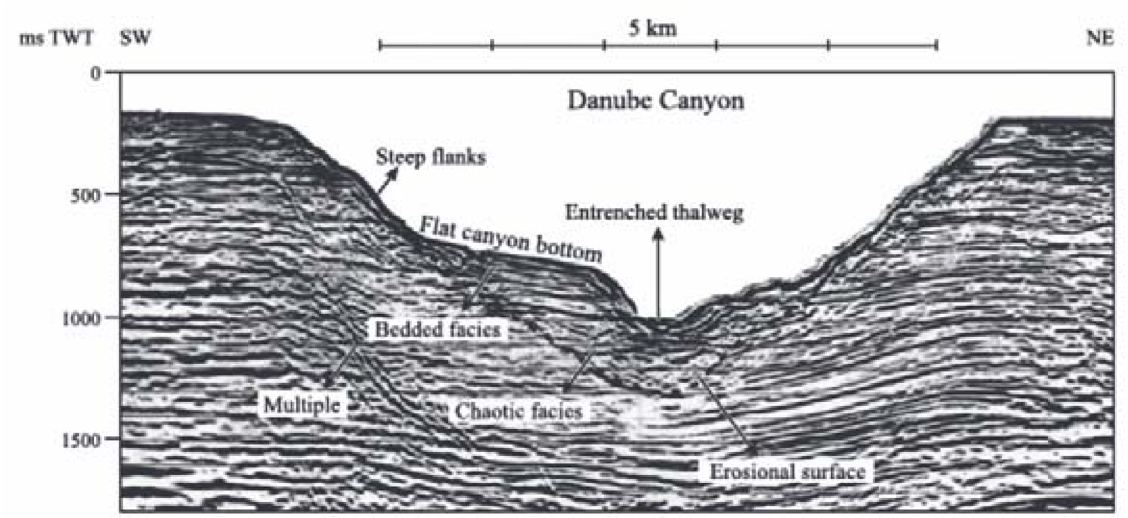


Figure 12. Sedimentary structure of the Danube Canyon (part of seismic industrial profile P941S-44) (from Popescu *et al.*, 2004). The line is situated across segment D. Canyon steep flanks are in prolongation of an ancient erosional surface (marked in dashed line), documenting a previous phase of canyon development. The infill consists of a chaotic seismic facies overlain by a high amplitude bedded facies, and is incised by the modern thalweg.

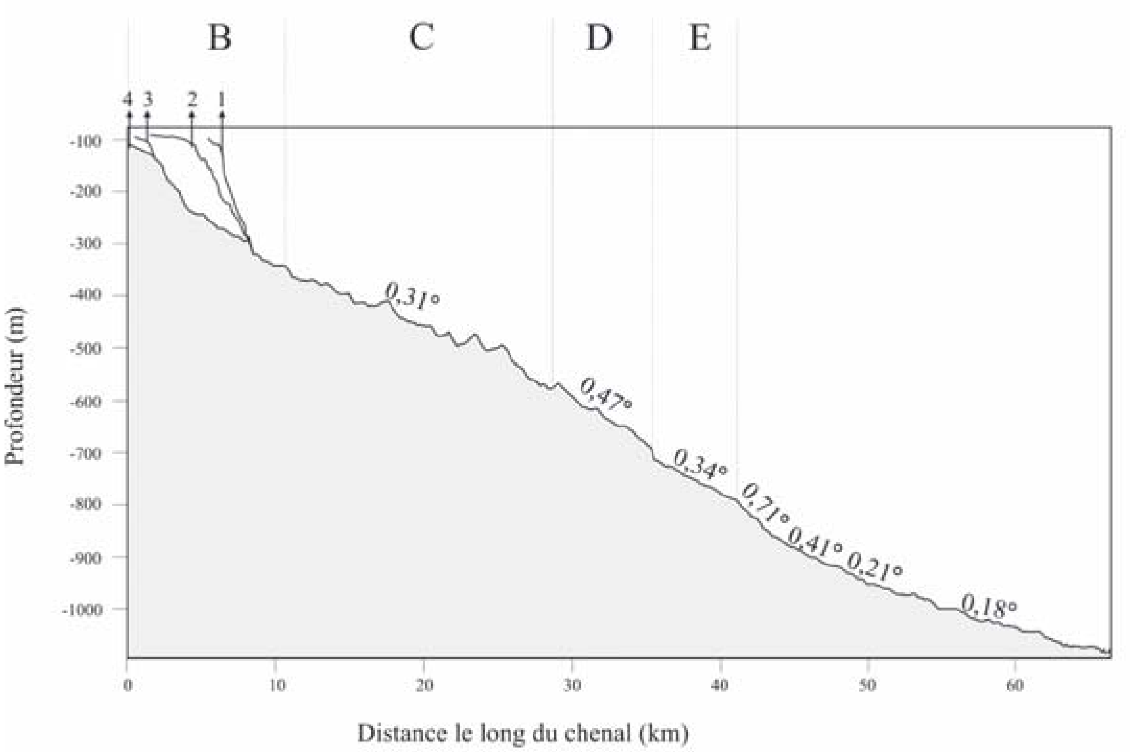


Figure 13. Longitudinal depth profile along the axial thalweg of the Danube Canyon/Channel (from EM 1000 multibeam data) (from Popescu, 2002).

The five segments of the canyon (Fig. 11), showing distinct features of morphology, orientation and gradient, are interpreted as zones of canyon advancement towards the coast. They also represent different maturity stages developed along the Danube Canyon valley.

Wong *et al.* (1994) consider that the Danube Canyon originated by processes of mass slumping produced on the continental slope and in time developed by subsequent retrograde slumping, during the following sea level rise episodes. The results of our studies indicate that canyon evolution was mainly due to erosion by heavily loaded bottom currents and/or by sediment flow generated during low sea levels stages. This idea is in agreement with the mechanism previously suggested by Shepard (1981), Pratson *et al.* (1994) and Pratson and Coakeley (1996).

There are significant morphology and structure features pointing out that the erosion processes generated the morphological features of the Danube Canyon. The axial thalweg is the erosional active zone of the canyon, where the canyon bottom downcutting resulted in trough entrenching. Sediment failures developed on the canyon lateral walls and headwalls due to the advancing entrenchment. These processes resulted in the canyon widening and promoted further landward shelf penetration by canyon headward erosion, along the sediment flow path and toward the source of the flow. Instability due to the presence of shallow gas in sediments and fault-controlled instability possibly contributed as additional mechanisms to cause sediment failures inside the Danube Canyon and its tributaries.

During the last Black Sea water-level lowstand the paleo-Danube River discharged close to the Danube Canyon head, maybe through a deltaic build-up (Fig. 14). During this most recent active stage of the canyon water, salinity was very low in the freshwater domain, which could have determined the initiation of hyperpycnal flows. In our opinion, the sediment-loaded flows related to the paleo-Danube River system stand for the main control factor of the Danube Canyon evolution.

3.3 Danube Canyon dating

The big unknown of the canyon evolution remains the age of this system. Currently, there is no independent age information either on the Danube Canyon incision and infill or on the fluvial buried channels we identified on the shelf. We can only assume that:

(1) The Danube Canyon is the most recent canyon related to the Danube River that developed in this part of the margin and its relief is preserved in the sea-floor morphology covered only by the Holocene deposits; therefore it was functioning during the last lowstand level of the Black Sea.

As a general rule, sea-level lowstands in the Black Sea do not necessarily correspond to global lowstands. The last sea-level lowstand in the Black Sea in particular, known as the "Neoeuxinian", was generally considered as matching the marine isotope stage 2 (Chepalyga, 1985 and references therein), but this correspondence was recently questioned (Major, 2002). The canyon was thus active during the last lowstand, but the age of this period is still uncertain.

(2) Buried fluvial incisions on the shelf are sealed only by the thin Holocene blanket, so that they formed during the last sea-level lowstand. Consequently, they are coeval to the youngest phase of canyon evolution.

(3) The evolution of the canyon is related to the evolution of the Danube Channel, since they are parts of a unique canyon-channel system that acted as a whole. Previous estimates of the age of the Danube Channel (Popescu *et al.*, 2001) were based on the correlation of the fan sequences with the sea-level curve (Wong *et al.*, 1994; Winguth *et al.*, 2000). The Danube Channel was active during the last lowstand but also during earlier glaciations low-stands (Wong *et al.*, 1994; Winguth *et al.*, 2000), as indicated by the succession of sediment bodies evidenced in the deep-sea fan system and by ^{14}C datations in the distal part of this system (Strechie-Sliwinski, 2007).

Consequently, it is conceivable that the youngest phase of evolution of the Danube Canyon corresponded to the last lowstand of the Black Sea, but canyon formation has also undergone previous stages. Unfortunately, age constraints for the canyon initiation are currently non-existent, and further investigation is necessary to solve this problem.

3.4 Control factors

Sediment input. It has long been observed that many submarine canyons were spatially connected to rivers on the continent (Twichell *et al.*, 1977; Fulthorpe *et al.*, 1999). Modelling also indicated that canyon evolution should be most active when sediment influx to the slope is greatest (Pratson and Coakeley, 1996).

The Danube Canyon is presently situated more than 100 km from the Danube mouths. As river sediment is trapped by southward currents along the coast and on the inner shelf, the present-day supply to the canyon is interrupted (Panin, 1996). This was not the case during lowstand times when part of the shelf was exposed, allowing direct fluvial sediment delivery to the shelf edge and to the Danube Canyon (Panin, 1989).

In order to clarify the spatial relationship between the river and the canyon, we attempted to recognize (1) the location of the paleo-Danube river and (2) the location of the paleo-shoreline during the last lowstand period in the Black Sea, which was implicitly the last active period of the canyon. We investigated seafloor morphology and shallow stratigraphy of the continental shelf in front of the Danube mouths with the purpose of tracking buried fluvial channels - as a diagnostic feature of ancient drainage systems, and wave-cut terraces – generally considered as indicating the proximity of the coastline.

Paleo-rivers. We identified numerous completely filled channels on the continental shelf down to –90 m water depth (Fig. 14). They reach 400-1500 m in width and 20-30 m in depth. Channels are sealed only by a thin mud drape parallel to the sea bottom. There is no independent indication of the age of these incisions. However, their stratigraphic position lying directly under the discontinuity at the base of the Holocene strongly suggests that they formed during the last lowstand.

The distribution of the buried channels clusters around two main directions that seem to correspond to two distinct drainage systems (Fig. 14).

The southern system points straight towards the Danube mouths and most probably represents the paleo-Danube River. On the outer shelf the river apparently splits into several arms similar to a deltaic structure comparable in size to the modern Danube Delta, and lies close to the Danube Canyon.

The origin of the northern system is so far uncertain.

Paleo-coastline. A submerged wave-cut terrace was mapped for about 100 km on the outer shelf, below water depths varying between –90 m and –98 m (Fig. 14). The variable depth of the terrace seems to be related to the presence of the canyon since the terrace is obviously shallowest around the canyon head. This could be the effect of the redistribution of wave energy when approaching the shoreline, as energy is focused on promontories and dispersed in gulfs.

The last lowstand paleo-coastline should thus have been situated between this submerged terrace and the deepest buried fluvial channels (Fig. 14).

Our data show (1) a great number of buried fluvial channels on the shelf that suddenly disappear below –90 m depth, and (2) a wave-cut terrace on the outer shelf, with an upper surface varying between –90 and –98 m. This is consistent with a major lowstand level situated somewhere around –90 m depth.

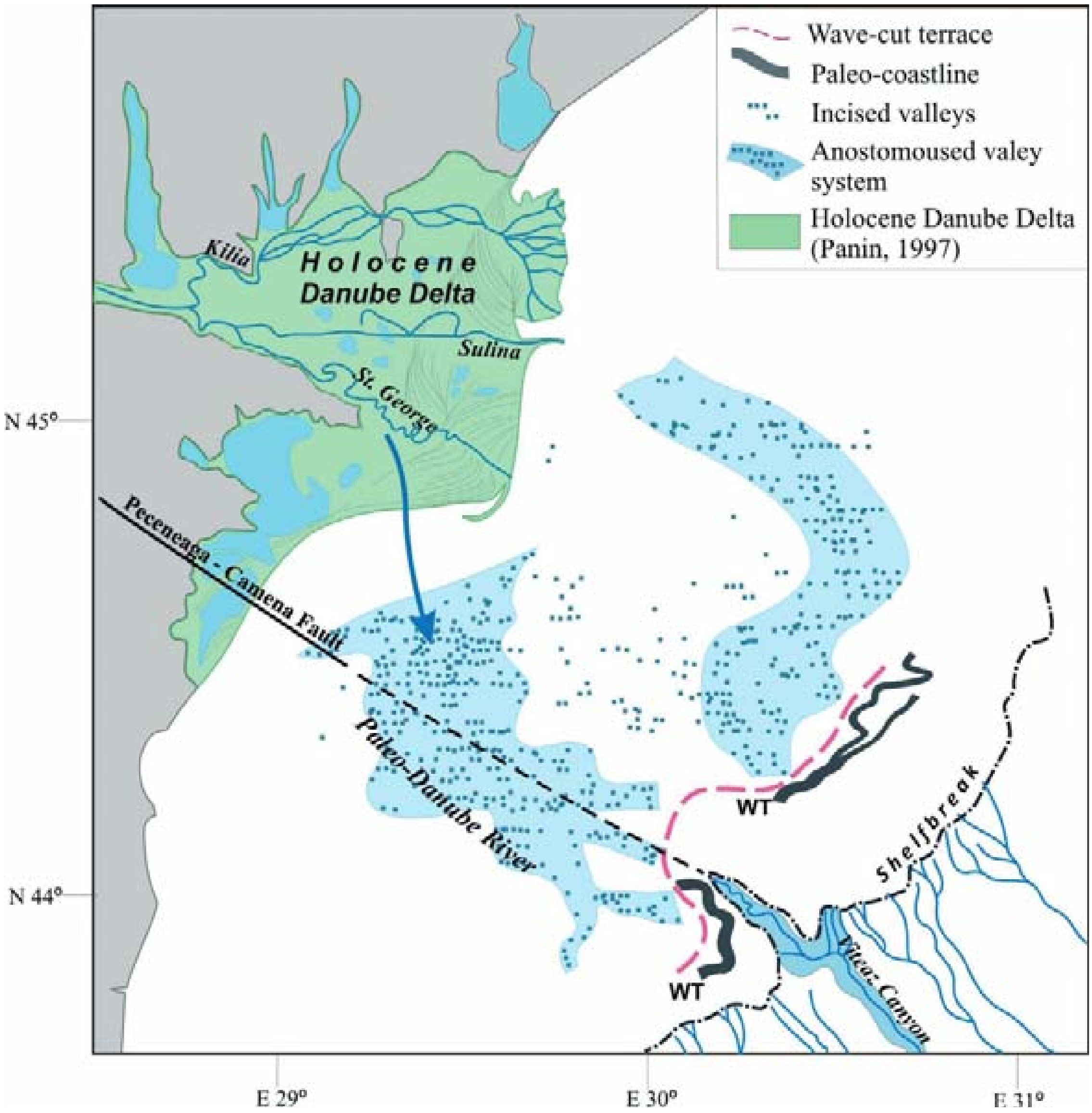


Figure 14. The hypothetical Paleo-Danube course on the exposed shelf area during the lowstands and the coastline location close to the shelf-break during the Last Glacial (from Popescu *et al.*, 2004).

Consequently, during the last water lowstand the Danube Canyon evolved in a shallow environment affected by high sediment supply. The paleo-coastline was forming a wide gulf in which it seems that two branches of the river were flowing. The canyon was entirely submerged and situated in the southern part of this gulf, in front of the paleo-Danube mouths and below the base of the wave-action zone, as attested by the position of the wave-cut terrace.

Meanwhile, it should be noted that the canyon developed under freshwater conditions that characterized the Black Sea during lowstands. The short distance between the river mouths and the canyon head, under environmental conditions that particularly favour the formation of hyperpycnal currents, suggests that the high sedimentary influx via the paleo-Danube was a major control on the canyon development.

Gas. The shelf edge of the north-western margin of the Black Sea contains evidence of abundant shallow gas and represents a zone of high fluid discharge (Vassilev and Dimitrov, 2000). Numerous gas seeps have been identified in this area (Egorov *et al.*, 1998). Most of them are located inside the Danube Canyon and along the landward prolongation of the canyon (Fig. 15). Gas seeps were also identified along the shelf break, on sub-recent faults north of the canyon, on the upper slope and in the upper Danube channel, usually related to failure areas.

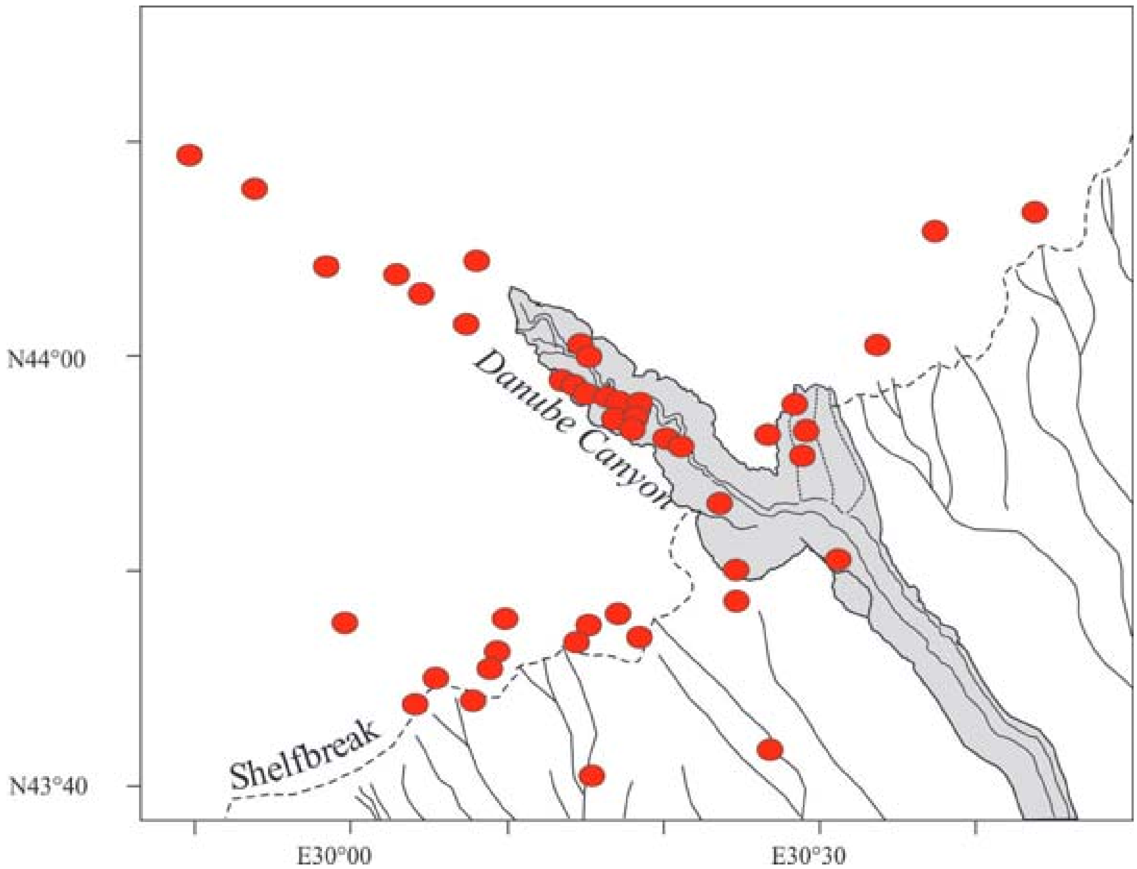


Figure 15. Location of gas seeps in relation to the morphology of the canyon area (from Popescu *et al.,* 2004, re-drawn after Egorov *et al.,* 1998).

Our seismic profiles show gas-related acoustic turbidity beneath the canyon, but also along its prolongation, commonly corresponding to the spatial distribution of the gas seeps. The gas area along the canyon has a limited lateral extent, so that the presence of the gas escape zones inside the Danube canyon is not due to exposure of a widespread shallow gas zone to the seafloor through erosion. In addition, the alignment of the gas seeps follows the same direction landward of the canyon (Fig. 15), which could be in relation with compression along a regional fault and thus a possible indication for a deep fault under the canyon. Moreover, profiles across major buried paleocanyons show acoustic turbidity clustering preferentially in the canyon areas (Popescu and Lericolais, 2003). It seems probable that the location of the gassy facies could have favored instability in the canyon area and possibly triggered sediment failures.

4. Conclusions

The Black Sea canyons characteristics depend on the relief energy of the coasts they are associated with. Considering their present-day dynamic characteristics, there are two main categories of canyons in the Black Sea: active canyons and inactive (inoperative) ones.

The active canyons are located in front of the mountainous Black Sea coasts (Caucasian and Pontic mountains), in zones with narrow shelf; they deeply cut this shelf, have steep walls and high gradient thalwegs and receive coarse-grained sedimentary load from closely discharging rivers or their deltaic built-up.

The northwestern and western part of the Black Sea, characterized by low, accumulative coasts and extensive shelf, is the region where the largest canyons (Danube and Dnieper canyons) are located. Only during the sea lowstands the paleo-rivers Danube and Dnieper extended across the shelf and fed the respective submarine canyons. The canyons formed in front of large shelf areas with low relief energy coast are generally supplied with finer-grained sediments and their deep-sea fan systems differ from the systems of mountainous coasts.

The Danube Canyon is a major erosional feature, deeply indenting into the shelf edge. The canyon consists of a main trough with steep flanks and a flat bottom incised by an entrenched thalweg. The sedimentary structure of the canyon shows evidence of previous cycles of erosion, followed by partial infilling and subsequently reincised by the modern canyon. Thus the canyon has not undergone a single-phase catastrophic formation, but a cyclic evolution with several erosion cycles of different magnitude.

On the basis of the geomorphological analysis, it appears that the main mechanism for canyon development was the sediment-flow-driven retrogressive erosion and even canyon-head wall failure. Sediment flows were most probably generated as high-density currents at the mouths of the paleo-Danube River, favoured by the low salinity conditions of the Black Sea basin during its lowstand phases. The high sediment influx in this part of the margin was therefore a major control on the canyon development, but other complementary controls (gas-related instability, deep fault control) could have contributed as well.

The Danube Canyon is connected to the Danube Channel and to channel-levee system on the Danube fan that extends to the abyssal plain down to 2200 m depth. The canyon represents the upper end of this system and acted as a gateway for transferring sediments between the shelf and the deep basin. High river discharge in the vicinity of the canyon, with probable hyperpycnal flow at the river mouths, suggests that a quasi-continuous river-canyon-fan channel system functioned in this part of the margin, ensuring highly effective transfer of the terrigenous sediments towards the deep sea.

---

* this chapter is to be cited as:

Popescu I., Panin N., Jipa D., Lericolais G., Ion G. 2015. Submarine canyons of the Black Sea basin with a focus on the Danube Canyon. pp. 103 - 121 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.

Submarine canyons of the Sea of Marmara

M. Namık Çağatay[1], Gülsen Uçarkuş[1], Kadir K. Eriş[1], Pierre Henry[2], Luca Gasperini[3], Alina Polonia[3]

[1] *İTÜ EMCOL and Geological Engineering Department, Faculty of Mining, İstanbul, Turkey*
[2] *CEREGE, Aix-Marseille Université, Collège de France, IRD, Europôle de l'Arbois, CNRS, Aix-en-Provence, France*
[3] *CNR, Institute of Marine Geology, ISMAR, Bologna, Italy*

Abstract

The Sea of Marmara canyons occur on the steep (10º-29º) slopes forming the boundaries of the ~1250 m-deep transtensional basins along the North Anatolian Fault zone. Most of the canyons were initiated by tectonic and erosional processes mainly during the Plio-Quaternary, when the basin margins were uplifted and deep basins subsided. Some, such as the İzmit, Şarköy and probably the Bosporus canyons, are localized by faulting. However, their morphology was modified by increased turbidity current and mass wasting activity during the Quaternary glacial low-stand periods. The Şarköy and Bosporus canyons occur at the extension of the Çanakkale (Dardanelles) and İstanbul (Bosporus) straits, and are associated with shelf valleys. Their morphology was strongly modified by erosional processes by passage of large water masses between the Mediterranean and Black Seas, especially during interstadials and meltwater phases. The sinuous North İmralı Canyon most probably developed at the shelf extension of the Kocasu River by turbidity currents.

Introduction

As in the case of all active tectonic continental margins around the world, the Sea of Marmara margins are incised by a number of submarine canyons (e.g., Clauson, 1973, 1978; Ergin *et al.*, 1991, 2007; Lewis and Barnes, 1999; Laursen and Normark, 2002; Chiang and Yu, 2006; Mountjoy *et al.*, 2009; Görür and Çağatay, 2010; Gasperini *et al.*, 2011; Zitter *et al.*, 2012; Lofi *et al.*, 2005; Harris and Whiteway, 2011; Würtz, 2012; Harris and Macmillian-Lawler, this volume) (Fig. 1). The Sea of Marmara, located on a continental transform-fault plate boundary between the Eurasian and Anatolian-Aegean plates, is a tectonically very active basin (Fig. 1). East of the Sea of Marmara, the North Anatolian Fault (NAF) forming the transform plate boundary splays into branches and accommodates a total of ~2.5 cm/year dextral motion (Straub and Kahle, 1999; McClusky *et al.*, 2002). Most of this motion occurs on the northern branch of the NAF (i.e., the Main Marmara Fault; Le Pichon *et al.*, 2001).

The Sea of Marmara consists of three transtensional basins; the Çınarcık, Central and Tekirdağ basins (Fig. 1). These basins are separated by the NE-trending Central and Western highs. The continental slopes connecting the shelf edge at ~ -90 m to the deep basins have slope angles ranging between 6° and 29°, and are incised by a number of submarine canyons with different morphological and tectonic features, such as İzmit Canyon (Gasperini *et al.*, 2011), North İmralı Canyon and canyons located on the southern slope of Tekirdağ Basin including the Şarköy Canyon (Ergin *et al.*, 2007; Zitter *et al.*, 2012).

The Marmara canyons were initiated by tectonic and erosional processes, and their evolution was strongly influenced by sea level changes and water-mass movements between the Mediterranean and Black Seas. They have acted as sediment conduits from shelf to the deep sub-basins, especially during the periods of low sea level.

In this study we describe the main canyon systems in the Sea of Marmara, including İzmit, North İmralı, south-western Tekirdağ Basin, Şarköy, and Bosporus canyons. We discuss the factors responsible for their evolution and their role as sediment conduits, using EM300 multi-beam, Chirp sub-bottom and multi-channel seismic and core data, and the manned submersible (Nautile) observations in the case of the İzmit Canyon.

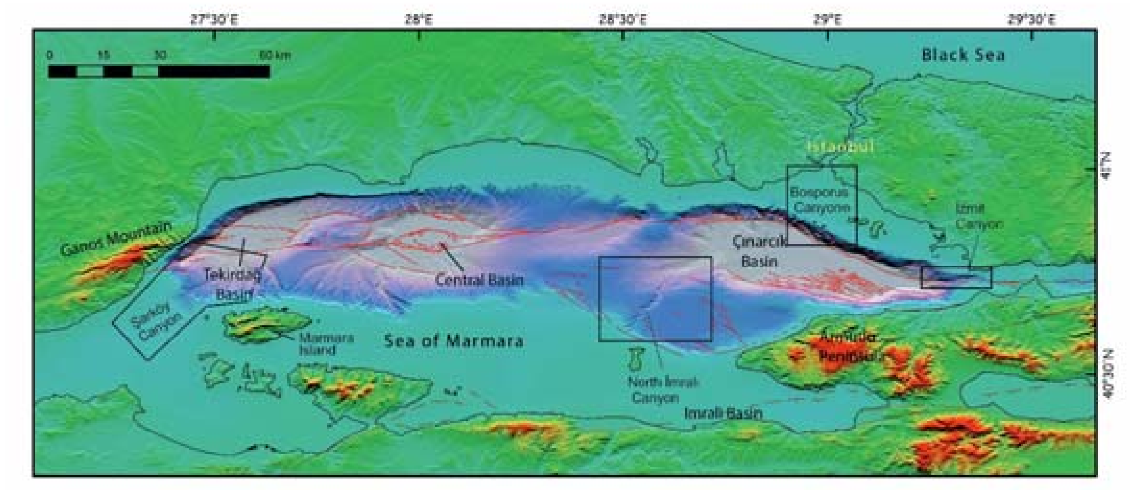


Figure 1. Morphotectonic map of Sea of Marmara showing the submarine canyons, active faults. EM300 bathymetry from Le Pichon *et al.* (2001) and active faults after Armijo *et al.* (2005).

Study Area

Geological setting

The Sea of Marmara is a tectonically active basin because of its location on the North Anatolian Fault (NAF) zone, a major dextral continental transform fault boundary between the Eurasian and Anatolian-Aegean plates (Fig. 1; Le Pichon *et al.*, 2001; Armijo *et al.*, 2005; Şengör *et al.*, 2005). It has a trough-like depression (i.e., the Marmara trough) located between a relatively narrow (~20 km wide) northern shelf and a 45 km-wide southern shelf (Fig. 1). The Marmara trough consists of three ~1250 m-deep strike slip basins; the Çınarcık, Central and Tekirdağ basins from east to west (Fig. 1). These sub-basins are separated by the NE-trending Central and Western highs, rising ~700 m above the deep basin floor. The continental slopes leading from the shelf break at ~ -90 m to the deep sub-basins are generally steep with slope angles ranging up to 29°. The steepest slope with a common slope angle of 20° to 26° is observed on the northern margin of the Çınarcık Basin, which is marked by northern branch of the NAF, the Main Marmara Fault (Le Pichon *et al.*, 2001). The southern slopes of the sub-basins are less steep with slope angles commonly varying between 6° and 16°.

The Sea of Marmara basin started forming as a shallow water lake, "Marmara Lake", within a broad shear zone during Late Miocene (Şengör *et al.*, 1985, 2005; Görür *et al.*, 1997). The basin is situated over the hydrocarbon bearing, Thrace fore-arc basin of Palaeocene-Middle Miocene age (Görür and Okay, 1996). The Marmara lake was occasionally flooded by Mediterranean waters during the Messinian and Pliocene, when the Çanakkale Strait probably also started its development (Çağatay *et al.*, 2006; Melinte-Dobrinescu *et al.*, 2009). The present-day morphology of the Sea of Marmara with its transtensional deep basins and transpressional highs, is the result of the Plio-Quaternary activity of the NAF (Şengör *et al.*, 2005; Bécel *et al.*, 2010; Grall *et al.*, 2010).

The most active northern branch of the NAF zone (the Main Marmara Fault) enters the Sea of Marmara in the Gulf of İzmit, and extends westwards to connect with the Ganos Fault and North Aegean trough. This branch follows the Izmit Canyon in the east, and cuts across the mouths of Bosporus and Şarköy canyons in the north and southwest, respectively (Fig. 1). The southern splays of the NAF occur north of İmralı (the South Marmara Fault; Le Pichon *et al.*, 2013) and in the Gemlik Gulf (Fig. 1). The NAF (mainly the northern branch) activity in the Sea of Marmara has created devastating earthquakes with 250-300 year average recurrence interval (Ambraseys and Finkel, 1991; Ambraseys, 2002, 2004). The latest earthquakes were the 1912 Mürefte-Şarköy earthquake (Mw 7.3) in the western shore and the 1999 Kocaeli (İzmit) (Mw 7.4) and Düzce (Mw 7.2) earthquakes in the eastern Sea of Marmara region.

Oceanographic setting

The Sea of Marmara is a transitional basin between the Aegean Sea and the Black Sea. It is connected with these adjacent seas via the Çanakkale (Dardanelles) and Istanbul (Bosporus) straits having sill depths of -65 and -35 m, respectively. The sea and its straits have a two-way flow system with an upper current of Black Sea waters (salinity: 18%) and a lower current of Mediterranean waters (salinity: 37%), with the pycnocline between the two water masses located at -20 m (Beşiktepe *et al.*, 1994).

The two-way connection of the Sea of Marmara with the adjacent seas commonly existed during the interglacial periods. Because of the shallow Çanakkale Strait sill depth, however, the Sea of Marmara was disconnected from the Mediterranean Sea and became a brackish-water lake during glacial periods (e.g., Çağatay *et al.*, 2000, 2009, 2015; Aksu *et al.*, 1999, 2002). One-way connection with a Black Sea outflow occasionally occurred depending on the climatic conditions. For example, strong intermittent Black Sea outflows to the Sea of Marmara and from there to the Aegean Sea occurred during the Melt Water Pulses and Dansgaard-Oeschger (D-O) events of Marine Isotope Stages 3 and 4 (MIS 3 and MIS 4) (Chepalyga, 1995, 2007; Bahr *et al.*, 2007; Çağatay *et al.*, 2015). During such events, the water level in the Marmara "lake" was controlled by the sill depth of the Çanakkale Strait, which was probably variable because of erosion and tectonic uplift of the sill (Yaltırak *et al.*, 2002; Çağatay *et al.*, 2009, 2015). During the glacial sea-level lowstands the Sea of Marmara shelves were subearially exposed.

The Marmara Submarine Canyons

The Sea of Marmara continental margins are marked by numerous submarine canyons. Their length is mostly limited by the width of the continental slope, and therefore commonly varies from 1 to 13 km on the basin margins (Görür and Çağatay, 2010; Zitter *et al.*, 2010), except for the İzmit, North İmralı and Şarköy canyons which are 36, 33.5 and 50 km long (Fig. 1). The southern slopes of the Tekirdağ and Central basins with low slope angles have the longest, widest (1-3 km) and deepest (up to 400 m) submarine canyons, whereas the northern continental slope of the Çınarcık Basin and northwestern slope of the Tekirdağ Basin with steep slopes (up to 29°), are short (1-2 km long) and narrow (few hundred metres) (Zitter *et al.*, 2012).

Most of the Sea of Marmara canyons have a straight course, extending from the shelf edge to the base of the continental slope. The only exception is the North İmralı Canyon on the southern slope of the Çınarcık Basin, which is sinuous (Fig. 1). All the canyons are associated with erosional gullies. Some canyons show branching towards the shelf edge. Others are characterized by arcuate head scars near the upper slope-shelf edge area, such as the Büyük Çekmece Canyon and the canyons located southern slope of the Tekirdağ Basin (Fig. 1). Some large canyons are located on the faults and are associated with submarine landslides (e.g., İzmit and Şarköy Canyons) near their junctions with the deep basins. The Şarköy and the Bosporus canyons are connected with the outlets of the Çanakkale and Bosporus straits on the shelf.

İzmit Canyon

This canyon is located on the northern branch of the NAF, connecting the İzmit Gulf with the Çınarcık Basin (Fig. 2A,B). The fault rupture of 1999 Kocaeli Eartquake (Mw=7.4) extended westward with decreasing lateral offset in the canyon (Çakır *et al.*, 2003; Ucarkus *et al.*, 2011; Gasperini *et al.*, 2011). The canyon bends from E-W to N-S at 200 m water depth. The length of the canyon below this bend is 33.5 km. The canyon has been offset ~100 m right-laterally by the NAF during the Holocene (Polonia *et al.*, 2004). Manned submersible (i.e., Nautile) dives in the canyon shows the presence of a 25 cm high fault scarp at 600 m water depth which may have formed as a part of the 1999 İzmit rupture (Gasperini *et al.*, 2011) (Fig. 2C). Microbathymetry data also show evidence of recent faulting at the canyon floor (Uçarkuş *et al.*, 2010).

Its location on the active fault, with the presence of the active fault scarp, strongly suggests a fault-controlled origin for the İzmit Canyon. It has been subsequently carved and modified, by subaerial erosion and turbidity currents during multiple glacial low-stand periods. Its northern wall in its lower course and mouth is bordered by Tuzla submarine landslide covering an area of 32 km^2 (Özeren *et al.*, 2010; Zitter *et al.*, 2012) (Fig. 2A. This landslide involves multi-phase rotational sliding of some 250 m-thick Devonian shales and a thin cover of Late Pleistocene-Holocene sediments. There is also a smaller landslide to the south of the canyon as can be seen in the bathymetry map and the seismic reflection line (Fig. 2A,B). These landslides on both flanks of the canyon were most probably triggered by the seismotectonic activity along the northern branch of the NAF.

The Nautile dive show that the canyon floor is commonly covered by bioturbated mud (Fig. 2D). General absence of recent erosion or sedimentary structures (e.g., ripples and scours) in the canyon floor is suggestive of recent low current activity and low sediment transport. However, in some parts of the canyon floor, N-S trending scarps formed by semi-consolidated sediment bed, are suggestive of differential erosion in the past. The canyon floor is colonized by a rich benthic fauna of bivalves, anemones, shrimps and foraminifera (Fig. 2C,D).

North İmralı Canyon

This is the only submarine canyon with a sinuous course in the Sea of Marmara (Figs 1 and 3A). The canyon is located on the relatively less steep (average slope angle: 10°) south margin of the Çınarcık Basin (Fig. 1). It is the second longest canyon in the Sea of Marmara, with a length of 33.5 km. The upper course of the canyon is situated between the shelf edge at -90 m and the -350 m, west of the İmralı Basin, and intercepted by the dextral North İmralı strike-slip fault with a vertical slip component. The canyon displays branching in the uppermost slope area near the shelf edge (Fig. 3A). It is generally accepted to represent the offshore extension of the Kocasu River, which represents the largest drainage network in the entire Marmara region, supplying 4.64 km^3/yr of water and 1.98 x 10^6 tons/yr of suspended sediment (EIE, 1993). It was recently suggested, however, that the canyon was connected with the outlet of the Gemlik "paleo-lake" during the last glacial period (Vardar *et al.*, 2014). Absence of high resolution seismic reflection and bathymetric data hinders tracing of the shelf extension of the canyon.

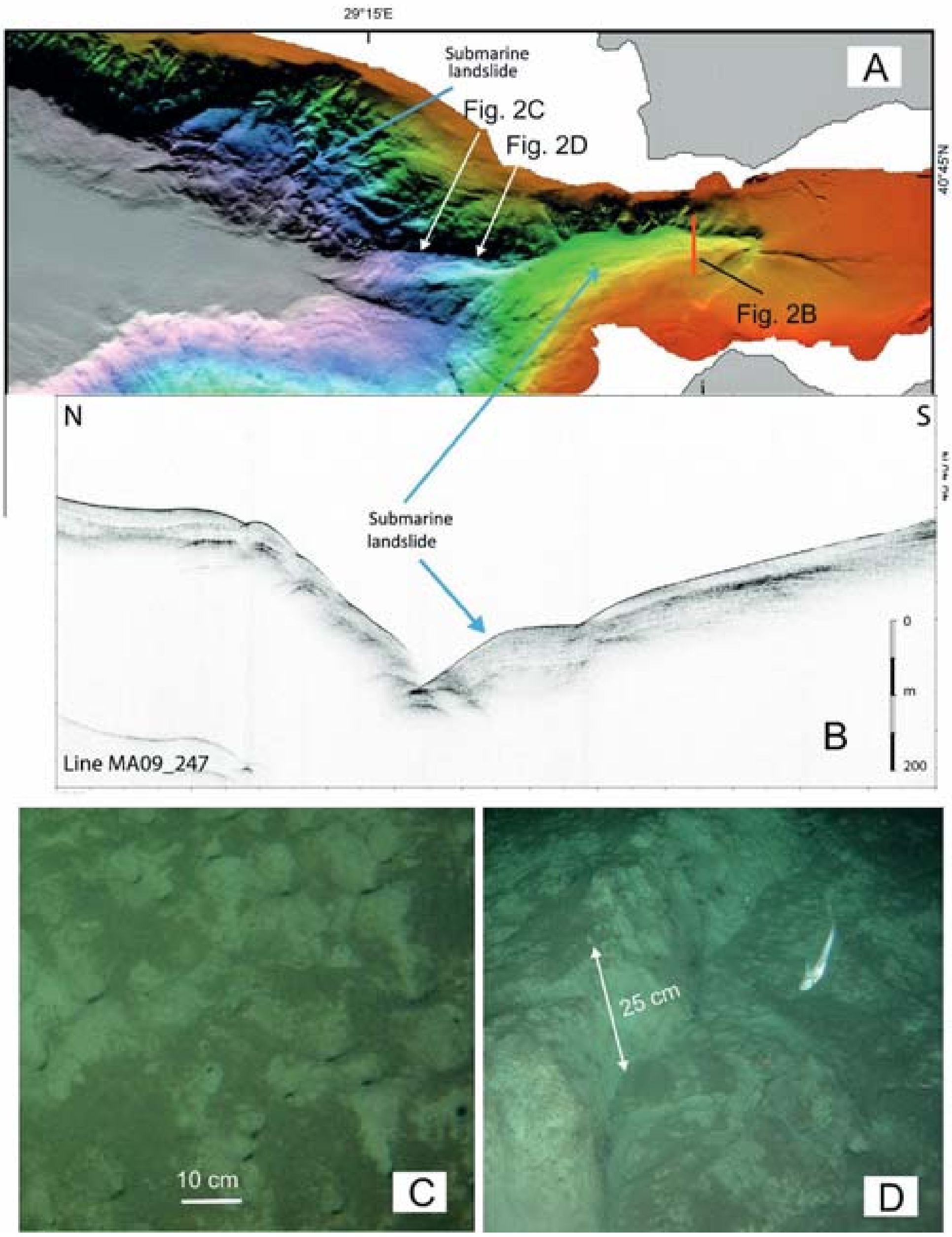


Figure 2. (A) Bathymetry map of the İzmit Canyon, located on the northern branch of the North Anatolian Fault. Also note the Tuzla submarine landslide west of the canyon, covering 27 km² area. For location see Fig. 1. (B) Chirp seismic reflection profile MA09-247nacross the canyon, showing a small landslide in the south. (C) View of submarine Izmit Canyon floor with bioturbated mud. (D) View of İzmit Canyon floor at -600 m, showing 25 cm high fault scarp, which is probably formed by multiple earthquakes.

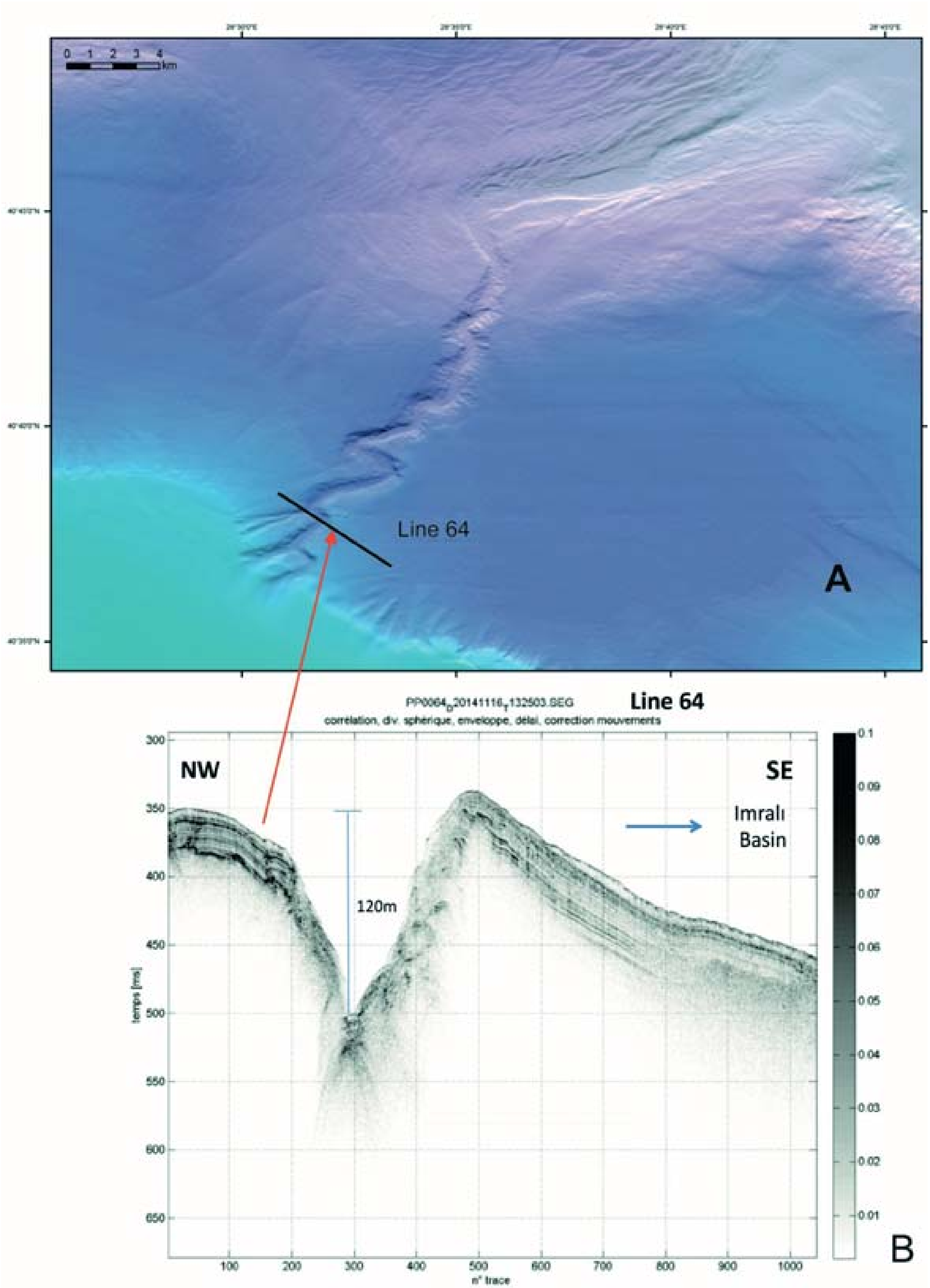


Figure 3. (A) Bathymetry map of the sinuous North İmralı Canyon, showing erosional scars on channel walls. (B) High resolution seismic section across the upper course of North İmralı Canyon, showing 120 m deep, V-shaped morphology of canyon. Note chaotic reflections on the eastern canyon wall indicating mass-wasting deposits and presence of layered sedimentary succession on channel banks.

The lower course of the canyon is located on a steeper margin between the İmralı and Çınarcık Basins. It makes a sharp bend towards the northeast at ~850 m water depth, near the eastern flank of the Central High, and opens to the southwestern corner of Çınarcık Basin with a 16.5 km-long and up to 6 km-wide channel (Fig. 3A). At the convex-inward part of the bend there is a point-bar deposition.

The walls of the North İmralı Canyon are marked by numerous gullies and erosional scours. The latter feature is mainly marked on the convex-outward part of the sharp bends in the sinuous channel. At water depths of 270-350 m, in the upper slope area, the V-shaped canyon channel is 100-120 m deep and show deposition of layered sediments on the banks (levees). Thickness of the bank sedimentary sequence increases to the east towards the İmralı Basin (Fig. 3B). The eastern canyon wall is occasionally represented by chaotic reflections suggesting mass-wasting deposits. The erosional and mass-wasting processes and deposition of the point bar in the canyon's channel all suggest strong current activity.

Even though the upper course of the canyon is cut by the North İmrali fault, both the seismic sections and bathymetry show very little fault control on its sinuous morphology. Such sinuous channels are widely believed to have been formed by turbidity currents (e.g., Shepard and Dill, 1966; Wynn *et al.*, 2007; Huang *et al.*, 2012). The North İmralı Canyon was probably carved by the Kocasu River and the turbidity currents especially during glacial low-stand periods when the base level was lowered and the river directly discharged its water and sediment load to the shelf edge and the upper slope.

Şarköy and other canyons on the south-western slope of Tekirdağ Basin

These canyons off the Marmara Island on the south-western slope of Tekirdağ Basin show branching with an upslope increase in the number of tributaries towards the shelf edge (Fig. 4A). The upper courses of the canyons are straight and branching, whereas the lower courses are curved. The Şarköy Canyon and two other canyons to the east appear to merge together and open to Tekirdağ Basin at ca -1100 m (Fig. 4A,B). Chirp subbottom profiles across the canyons and cores located at the canyon mouths show the presence of debris flow deposits and coarse shelly sand beds (Fig. 4B,C) (Zitter *et al.*, 2012). The last debris flow deposit occurs within the marine unit, which has been deposited in the last 12.6 ka BP.

The western flank of the Şarköy canyon is formed by the Ganos Landslide Complex with an area of 80 km^2 (Zitter *et al.*, 2012) (Fig. 4A). The landslide complex shows an undulatory (wavy) surface and retrogressive slope failures. The general strike of undulations are perpendicular to the slope, which suggests several possibilities, including sediment waves formed by the undercurrent of Mediterranean water, slow downslope sediment sliding, creeping, and/or lateral spreading (Fig. 4A,B).

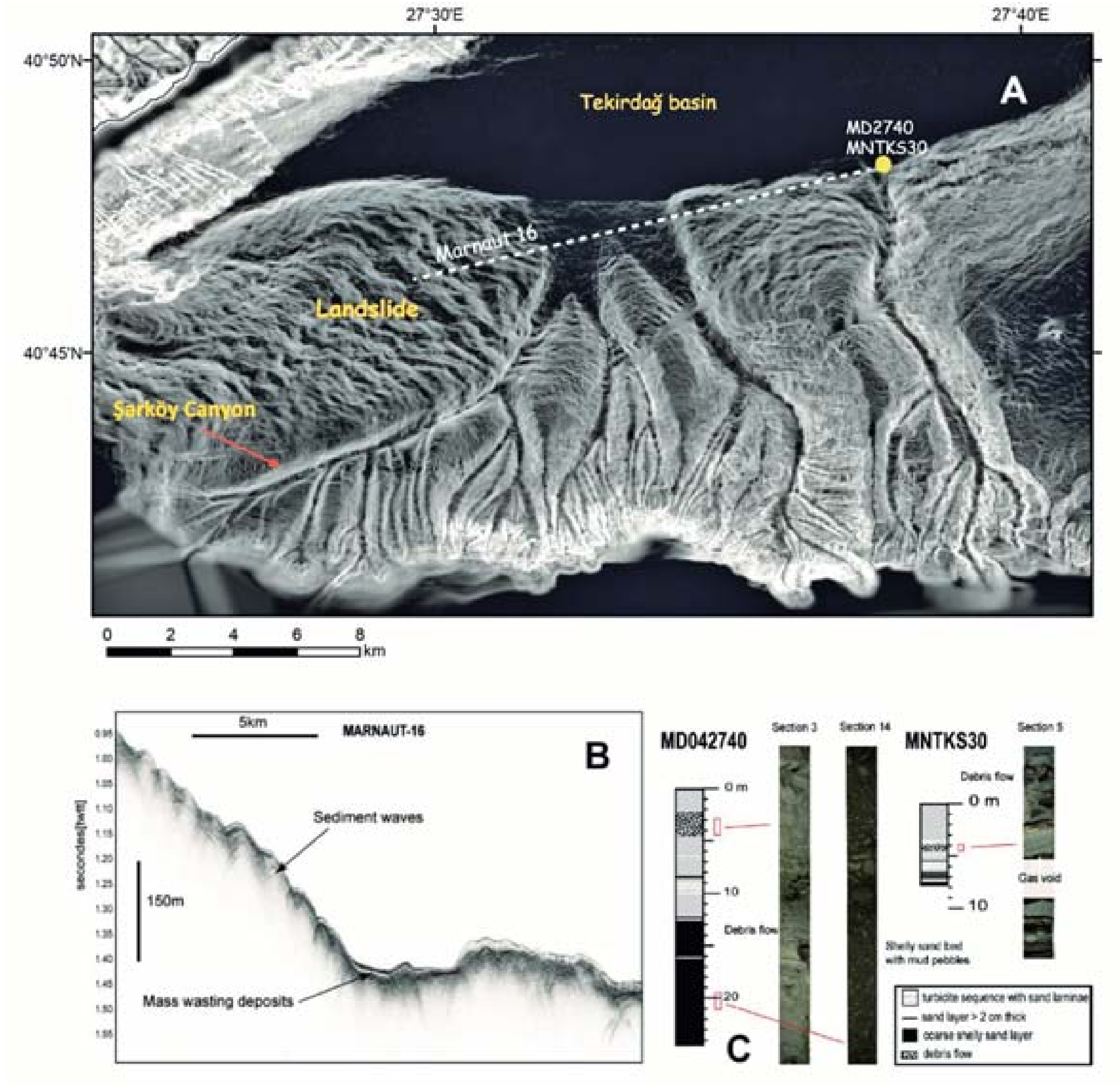


Figure 4. (A) Slope gradient map of north of Marmara Island, southern slope of Tekirdağ Basin, showing the canyons including the lower course of the Şarköy Canyon. The canyons appear to merge and open to Tekirdağ Basin. Also seen is Ganos Landslide Complex to the west overlying strike slip Ganos Fault. For location see Fig. 1. (B) Chirp subbottom profile across the slope of the landslide and mouths of canyons, showing the transparent mass-wasting deposits. (C) Cores located at the mouth of canyons containing debris flow deposits (modified after Zitter *et al.*, 2012).

The 50 km-long Şarköy Canyon is located at the continuation of the Sea of Marmara outlet of the Çanakkale Strait, and connects the ~60 m-deep strait's channel with the 1100 m-deep south-western corner of Tekirdağ Basin (Figs. 1, 5A). The canyon is responsible for transporting the saline and dense Mediterranean waters as the undercurrent to the deep Tekirdağ Basin. It is intercepted at its mouth in the south-western Tekirdağ Basin by the strike- slip Ganos Fault segment of the NAF and further up by the subparallel strike-slip faults branching off the Ganos Fault and having a reverse component (Fig. 5B). The lower course of the Canyon is underlain near its mouth by the Ganos Landslide Complex, which partly covers the Ganos Fault (Zitter *et al.*, 2012). The canyon bends towards northeast at ~ -400 m, and then follows the western edge the Ganos Landslide, turning north-northeast (Fig. 5A). Several north-directed tributaries join the Şarköy Canyon from the slope off the Marmara Island (Fig. 4A).

The Ganos Landslide Complex is characterized by high microseismic activity displaying normal and strike-slip focal mechanisms (Örgülü, 2011). The seismicity is interpreted to show NE-SW extension and sliding of the Ganos Landslide Complex over a NE-dipping crustal detachment surface (Zitter *et al.*, 2012). The absence of high resolution multi-beam bathymetric data in the upper course of the canyon hinders a detailed morphological analysis of the canyon's channel. However, seismic reflection data show that the canyon has a U-shaped profile in its upper course close to the Çanakkale Strait and a V-shaped profile in its lower course close to the Tekirdağ Basin (Ergin *et al.*, 2007). The seismic data display also slope failures on both eastern and western walls of the canyon.

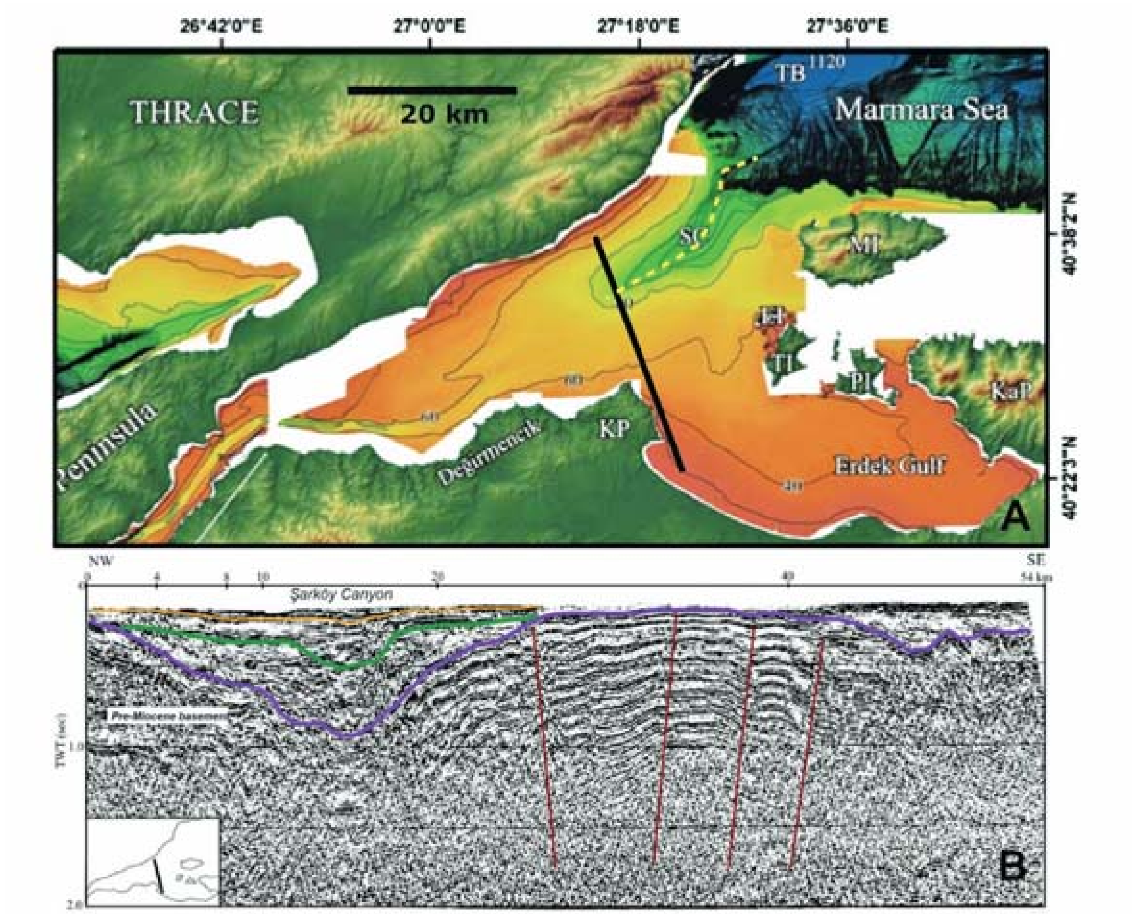


Figure 5. (A) Digital elevation model-bathymetry map of Şarköy Canyon (modified after Gökaşan *et al.*, 2010). For location see (B) Multi-channel seismic profile across Şarköy Canyon showing seismic stratigraphic sequences. Unit 1 is probably of Early Pliocene age above a possible Messinian erosional surface (slightly modified after Ergin *et al.*, 2007).

The thalweg of the canyon is draped by 2.5-3 m-thick Holocene mud consisting of subequal amounts of silt and clay with minor sand (Ergin *et al.*, 2007). The Holocene sedimentation rate in the thalweg of the channel varies from 20 and 25 cm/kyr. The average grain size of the surficial sediment in the canyon decreases with water depth. This suggests a downslope decrease of the current strength with deepening and widening of the canyon channel (Ergin *et al.*, 1991). The cores recovered from the outer part of the canyon channel near its mouth contain coarser sediments with up to 55% sand and gravel (Ergin *et al.*, 1991). The coarse grain fraction of the surface sediments includes shells of pelecypods, gastropods, foraminifera, ostracods, echinoids, bryozoans and coralline algae.

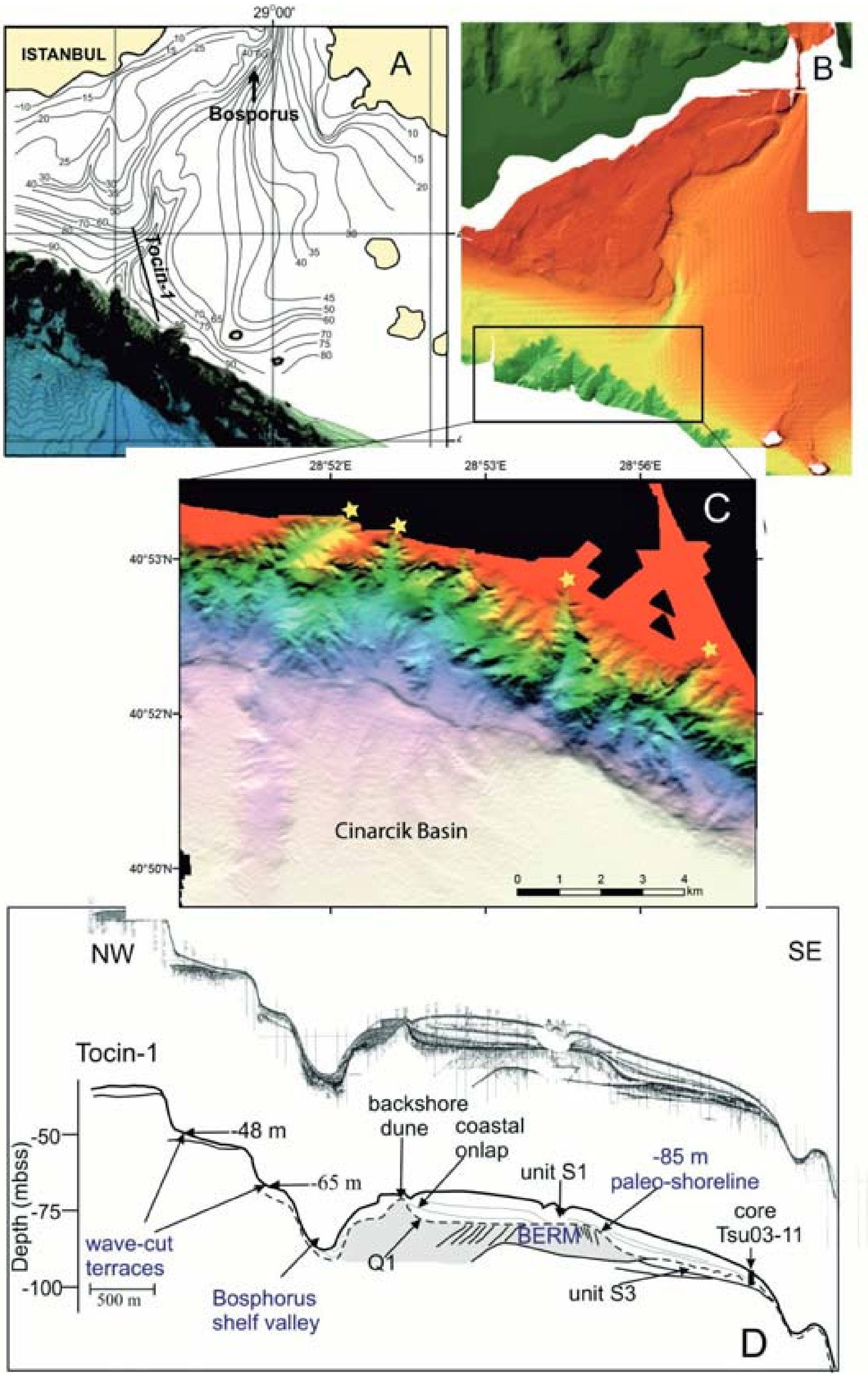
Offshore Multi-channel seismic data and onshore stratigraphic studies suggest that the geological evolution of the Şarköy Canyon and the Çanakkale Strait extends back to the Late Messinian when the Mediterranean was desiccated and then flooded during the Pliocene (Lofi *et al.*, 2005; Çağatay *et al.*, 2007; Melinte-Dobrinescu *et al.*, 2009) (Fig. 5B). During the Pliocene, the NAF as a major strike-slip fault, started its activity in the region and caused strong deformation around the Şarköy Canyon (Okay *et al.*, 1999; Seeber *et al.*, 2004; Armijo *et al.*, 2000; Şengör *et al.*, 2005) (Fig. 5B). The most marked evidence of this deformation is the uplift of the ~1000 m-high (above sea level) Ganos Mountain, north of the Ganos transpressional bend. The canyon appears to have been considerably modified since the Pliocene by cyclic glacio-eustratic sea level changes. During especially the glacial periods when low lake levels existed in the Sea of Marmara, the shelf and the uppermost slope regions were exposed to subaerial erosion and the erosional and depositional activities in canyons increased. The evidence of this increased canyon activity is observed by the more frequent submarine landslides, debris flows and turbidites found in cores recovered from the canyon mouths and deep basins (Görür and Çağatay, 2010; Zitter *et al.*, 2012; Grall *et al.*, 2013; McHugh *et al.*, 2014) (Fig. 4C).

Low lake levels between 90 and 110 m below the present sea level prevailed in the Sea of Marmara during the Last Glacial Maximum (LGM) and late glacial, which have been documented by the presence of shoreline terraces and wave-cut erosional features (Ergin *et al.*, 1997; Aksu *et al.*, 1999; Eriş *et al.*, 2011). Paleoshorelines at -85 m corresponding to the last lacustrine stage before the last marine connection 12.6 ka BP are present on the northern shelf (Çağatay *et al.*, 2003; 2009; Eriş *et al.*, 2011).

Bosporus Canyon

The Bosporus canyon connects with the shelf extension of the Bosporus Strait's outlet, i.e., the Bosporus shelf valley, on the northern shelf of the Sea of Marmara (Figs. 1, 6A,B,C). The Bosporus shelf valley is broadly sinuous and winding (Fig. 6A,B). It joins the Bosporus Canyon at 60-70 m depth on the outer shelf. In the inner to mid-shelf area, the Bosporus shelf valley includes a channel-levée complex of early Holocene age (Eriş *et al.*, 2007). Near the junction with the Bosporus Canyon, the Bosporus shelf valley is U-shaped and displays some wave-cut terraces at -48 m and -65 m, and a berm at -85 m (Fig. 6D). The last feature is indicative of a paleoshoreline of the Marmara "Lake" (Eriş *et al.*, 2011), observed in many locations on the northern shelf of the Sea of Marmara and dated ~12 ka BP (Çağatay *et al.*, 2003, 2009; Polonia *et al.*, 2004). The unconformity surface together with the berm is draped by a Holocene marine mud unit.

Figure 6. (page opposée) (A) Contoured bathymetry map of the northern shelf and northern part of the Çınarcık Basin, showing the sinuous Bosporus shelf valley and steep slope (Eriş *et al.,* 2011). (B, C) Multibeam bathymetry maps showing canyons (stars in map (C) on the slope and the shelf extension of Bosporus Canyon and Bosporus Strait's outlet (Bosporus shelf valley) (modified after Tur, 2015). (D) TOCIN Seismic reflection profile near the junction between Bosporus shelf valley and the Bosporus Canyon. The profile shows wave cut terraces and a berm representing paleoshoreline dated ~12-13 ka BP (modified after Eriş *et al.*, 2011).



29°00'
ISTANBUL
A
Bosporus
Tocin-1
B
C
28°52'E
28°53'E
28°56'E
40°53'N
40°52'N
40°50'N
Cinarcik Basin
0 1 2 3 4 km
NW
SE
Tocin-1
Depth (mbss)
-50
-75
-100
500 m
-48 m
-65 m
wave-cut terraces
Bosphorus shelf valley
backshore dune
coastal onlap
Q1
unit S1
BERM
-85 m paleo-shoreline
core Tsu03-11
unit S3
D

The canyon's remaining course is located on the very steep (20-29º slope angle) northern continental slope of the Çınarcık Basin (Fig. 6C). The canyon channel conveys a slow up canyon flow of Mediterranean waters towards the Black Sea. Below the junction with the Bosporus shelf valley, the Bosporus Canyon on the steep continental slope becomes gradually wider as it approaches the 1250 m deep Çınarcık Basin. Within the channel thalweg, the surficial sediments are mostly mud, consisting of subequal amounts of clay and silt, and locally gravelly mud (Ergin *et al.*, 1991). The sediments become finer down the canyon, with a relative increase in the clay-size fraction, suggesting northward increase in the current strength, approaching the Bosporus Strait. The shell (biogenic carbonate) content of the sediments decreases with water depth in the canyon. The shells consist of coralline algae, pelecypods, gastropods, echinoids, bryozoans and foraminifera. The deeper part of the canyon channel (>70 m depth) is characterized by a pelecypodal-foraminiferal assemblage (Ergin *et al.*, 1991).

The Bosporus Canyon is likely to have a similar origin to that of the Şarköy Canyon, although the faulting control is not so clear and the age of the Bosporus channel is disputable. WNW–ESE trending extensional faults east and west of the Bosporus shelf valley have been observed on seismic reflection lines (Çağatay *et al.*, 2009; Görür and Çağatay, 2010) and tectonic and faulted-valley origin of the Bosporus has been proposed (Yılmaz and Sakınç, 1990; Gökaşan *et al.*, 1997; Şengör, 2011). The oldest dated sediments of the present-day Bosporus channel are so far 26 ka BP (Çağatay *et al.*, 2000). However, the sediment infill belonging to much older periods may have been swept by the strong currents involving inflows and outflows through the strait, or may have been preserved only in the depressions in the basement of the Bosporus channel, which have yet to be drilled.

Flooding of the Marmara "Lake" by torrential Black Sea outflows, especially during the interstadials and melt water pulses, was probably effective in carving of the Bosporus shelf valley and Bosporus Canyon. Such strong Black Sea outflow events have been reported during the interstadials of Marine Isotope Stages 4 and 3 and the Melt Water Pulses during 16-15 ka BP (Chepalyga, 1995, 2007; Bahr *et al.*, 2007; Çağatay *et al.*, 2015) and just after the Younger Dryas; the last event is evidenced by the formation of the channel-levee complex in the Bosporus shelf valley (Eriş *et al.*, 2007).

Conclusions

The Sea of Marmara canyons occur on the steep slopes (>10º) of the ~1250 m-deep transtensional basins between the splays of the right lateral North Anatolian Fault. They are commonly short (1-3 km), except for the the İzmit, North İmralı and Şarköy canyons which are 36, 33.5 and 50 km long. The canyons started forming by tectonic and erosional processes mainly during the Plio-Quaternary, when the basin margins were uplifted and the deep basins subsided. Some of the canyons such as the İzmit, Şarköy and probably the Bosporus canyons occur on faults or fault zones. However, their subsequent evolution was strongly influenced by climatically controlled cyclic sea (lake) level changes. The Şarköy and Bosporus canyons at the extension of the Çanakkale (Dardanelles) and Bosporus straits have evidenced passage of large water masses between the Mediterranean Sea and Black Sea, and their morphology was strongly modified by erosional and depositional processes, especially during interstadials and melt water pulses, when one-way flow regime operated through the straits and the Sea of Marmara. The sinuous North İmralı Canyon most probably developed at the shelf extension of the Kocasu River by erosive activity of the turbidity currents. Mass wasting and turbidity current activity in the canyons were more frequent and effective during the periods of low sea level and transition from lacustrine to marine conditions in the Sea of Marmara.

Acknowledgements: The data used for this study were collected during several cruises over the last 15 years, on board of research vessels Le Suroit, L'Atalante, Marion Dufresne, Urania, MTA Seismic-1, and Pourquoi Pas? and by the manned submersible Nautile and the Victor 6000 ROV. The authors thank the captains and crews of these research vessels and pilots of Nautile and Victor 6000.

---

* this chapter is to be cited as:

Çağatay M.N., Uçarkuş G., Eriş K.K., Henry P., Gasperini L., Polonia A. 2015. Submarine canyons of the Sea of Marmara. pp. 123 - 135 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.

Currents and sediment fluxes in canyons and deep outflow channels at the southwest Cretan margin (Eastern Mediterranean)

Kontoyiannis H., S. Stavrakakis, A. Karageorgis and V. Lykousis

Hellenic Centre for Marine Research, Greece

Abstract

A general picture is provided for the deep current and the lithogenic sediment-flux regime within the Samaria Canyon, south of Crete, and the deep channel to the west of Crete were Cretan Dense Water can potentially outflow into the Ionian Basin. The relevant phenomenology concerns the periods a) 1997-1998, at the west Cretan outflow channel, b) 2005-2006, at the Samaria Canyon and c) 2011-2012, at the west Cretan outflow channel. In 1997-1998, a strong southward bottom current (mean speed ~15 cm/sec) was associated with the dense water plume in the Cretan outflow channel. In 2005-2006, the bottom (1600 m) and the intermediate (1000 m) flows in the Samaria Canyon were topographically controlled with weak mean speeds (~2 cm/sec), the lithogenic fluxes were very weak, lower than 100 mg m^{-2} d^{-1}, with an indication of a possible lithogenic input from the land in the winter period. In 2011-2012, no dense plume was observed in the west Cretan outflow channel, the bottom flow was southward along bottom contours and very weak (mean speed ~1-2 cm/sec) while the lithogenic fluxes were lower than 120 mg m^{-2} d^{-1}.

Introduction

Most submarine canyons are located at the continental margins of the world ocean. Therefore, they are the natural conduits of settling mass that is transferred from the continental shelf to the deep sea (Gardner, 1988; Huang *et al.*, 2014). The oceanographic published record includes many multidisciplinary studies combining analyses on hydrodynamics, particulate matter dynamics and settling fluxes in canyons. Some informative studies on European submarine canyons exist for the Cap Ferret canyon (Ruch *et al.*, 1993), the Grand-Rhône canyon (Durrieu de Madron, 1994; Durrieu de Madron *et al.*, 1999; Palanques *et al.*, 2008) and the Cap de Creus canyon (Canals *et al.*, 2006; Lastras *et al.*, 2007). The deep outflow channels are in fact canyon-like bottom structures in which newly formed dense-water plumes cascade towards the deeper oceanic layers. These dense plumes often originate in shallow marginal seas and then flow over a sill into the deep ocean, as is the case of the Cretan Dense Water outflowing from the Cretan Sea into the Ionian and the Levantine basins (Figure 1, Figure 2).

The HCMR (Hellenic Centre for Marine Research) participated in EU projects, such as PELAGOS (Insights into the hydrodynamics and biogeochemistry of the south Aegean Sea, Eastern Mediterranean) and MATER (Mass Transfer and Ecosystem Response) in the mid and late 1990s, that included investigations on the Cretan deep outflows, whereas in 2005 and 2006 its participation in the HERMES project (Hotspot Ecosystem Research on the Margins of European Seas) was specifically targeted on issues related to the Samaria and the Lithinon canyons south of Crete

(Figure 2). HERMES involved the acquisition of time series of currents and sediment-trap fluxes in these canyons along with basic hydrographic surveys in the wider study area south of Crete. In 2011-2012, in the framework of the HERMIONE project (Hotspot Ecosystem Research and Man's Impact on European Seas), HCMR continued with the simultaneous investigation of the deep flows and the sediment-trap fluxes in the deep outflow channel to the west of Crete (Figure 2).

Previous oceanographic work in the specific study area south of Crete involves basically the hydrographic investigations in the framework of the POEM (Physical Oceanography of the Eastern Mediterranean) project in the period from the late 1980s to the mid 1990s. POEM focused on the sub-basin circulation structures in the East Mediterranean, including the area south of Crete, thus providing valuable information on the major circulation structures affecting our study area (Robinson *et al.*, 1991). Previous work that refers to the Samaria and Lithinon Canyons is by Alves *et al.* (2007) in which it is suggested that their development on the slopes can be related to the presence of sub-aerial canyons onshore and friable substrate rocks on the continental slope. Other previous work refers in the area refers to the submarine slides in the Lithinon Canyon (Huson and Fortuin, 1985), the relationships between enzymatic activities and organic carbon in sediments (Polymenakou *et al.*, 2008), and the biochemical composition of sedimentary organic matter (Pusceddu *et al.*, 2010).

The main aim of this paper is to provide an overall picture of the deep currents and sediment fluxes in these deep channels over a period from the late 90s, i.e., the years of the MATER project, to the mid 2000, i.e., 2005 and 2006 during the HERMES project, to the period 2011-2012 during the HERMIONE project. The deep current meter and sediment-flux data in these canyons are accompanied with hydrographic data of profiles of physical water characteristics.

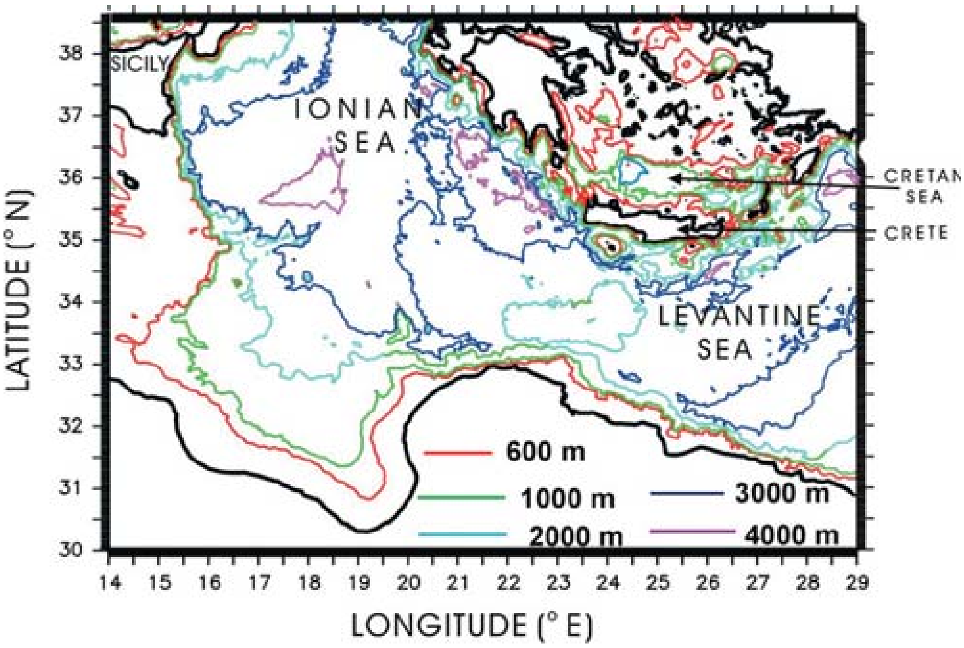


Figure 1. Gross bottom topography of the Cretan margin in the Eastern Mediterranean.

Field sampling and methods

In all the projects mentioned above, the hydrographic work was carried out via a Sea-Bird Electronics 11*plus* CTD profiler that was lowered in the water column down to a depth of ~1-5 m above the sea bottom. In most, but not all, of the hydrographic surveys additional sensors of light transmission and dissolved oxygen sensors were attached to the Sea-Bird CTD underwater unit. The light transmission measurements were acquired with a Chelsea ALPHA*tracka* MkII sensor that measures the intensity of a well-collimated light beam of 660 nm at 25 cm from its emission point. The light transmission measurement is expressed in terms of the percent ratio of the light intensity at 25 cm away from the emission to the light intensity at the emission point.

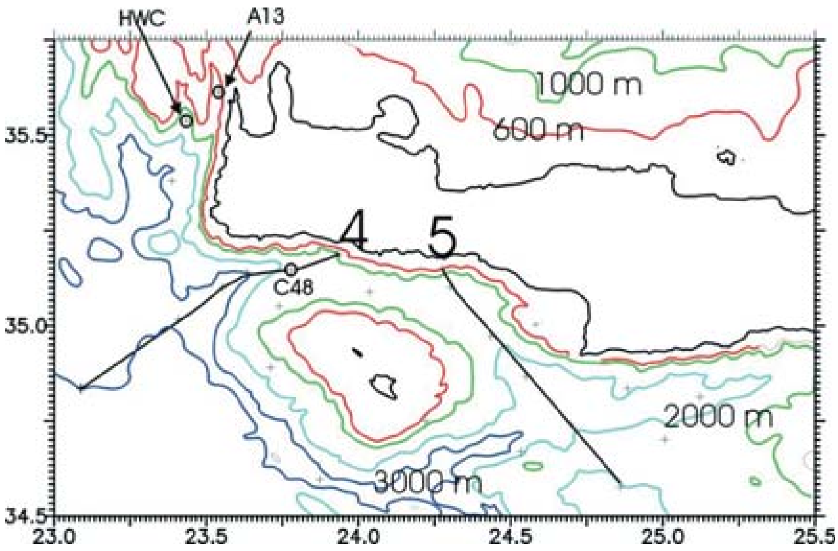


Figure 2. Expanded view of the study area to the southwest of Crete. The bold lines noted as '4' and '5' indicate the axes of the Samaria and the Lithinon Canyons respectively. Stations A13, HWC and C48 are mooring locations during the MATER (1997-1998), the HERMIONE (2011-2012) and the HERMES (2005-2006) EU projects, respectively. All crosses indicate CTD positions during the HERMES project. The 600-m (red) bottom contours to the northwest of Crete indicate the location of the sill between the Cretan Sea and the Ionian Sea. Locations A13 and HWC are in the channel of the Cretan Dense Water outflow to the west of Crete, which is through the so-called Antikythera Strait.

The moorings were instrumented with sediment traps (PPS3/3 Technicap with 0.125 m^2 collecting area and 12 receiving cups) and Aanderaa current meters (type RCM8 and RCM9). The near-bottom traps and current meters were positioned about 15 m above the bottom. The analyses of the sediment-trap material was for organic and inorganic carbon, biogenic silica and lithogenic fraction. We will report here on the lithogenic fraction, which in general occupies the greatest percentage of the total sediment content.

The preparation of the sediment traps and sample processing followed the protocol of Heussner *et al.* (1990). Briefly, upon recovery of the trap, samples were stored at 2 °C in the dark until treatment. Swimmers were removed by sieving the sample through 1 mm nylon mesh, and then by hand under a light microscope using fine tweezers. The subsampling was obtained using a peristaltic pump (Perimatic Premier, Jencons Ltd.), an orbital stirrer, a round-flask and glass beakers. The subsamples were filtered onto different filter types (e.g. Millipore 0.45 μm nominal pore size for opal and Whatman GF/F 0.7 μm nominal pore size for organic carbon) and rinsed with filtered seawater before they were analyzed. Total mass fluxes were calculated for all samples. The major constituents were determined according to Monaco *et al.* (1990) as follows: opal (biogenic silica) was determined with extraction of silica into 2M Na_2CO_3 solution at 85 °C for 5h (Mortlock and Froelich, 1989), organic matter was determined by doubling particulate organic carbon values (Gordon 1970), the carbonate content was calculated as inorganic carbon x8.33, the lithogenic component (quartz, feldspars, calcite, aluminosilicates, heavy minerals) was calculated by subtracting the concentration of the other three constituents from the total weight.

RESULTS

a. Hydrography and currents in the late 1990s

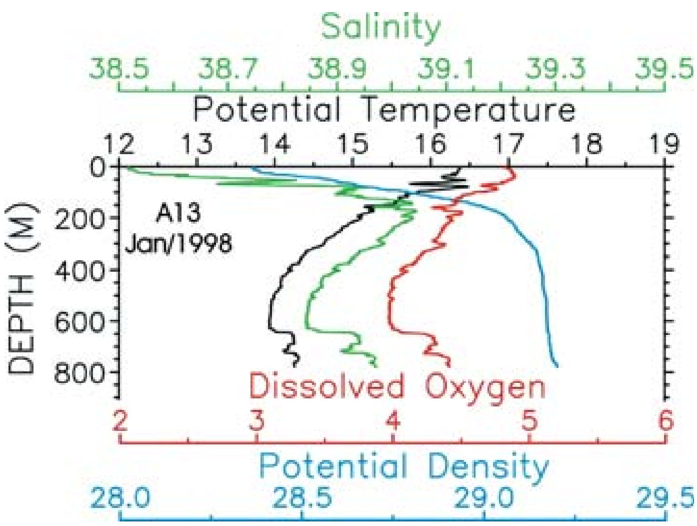


Figure 3. Profiles of salinity, potential temperature, dissolved oxygen and potential density at Station A13 in January 1998.

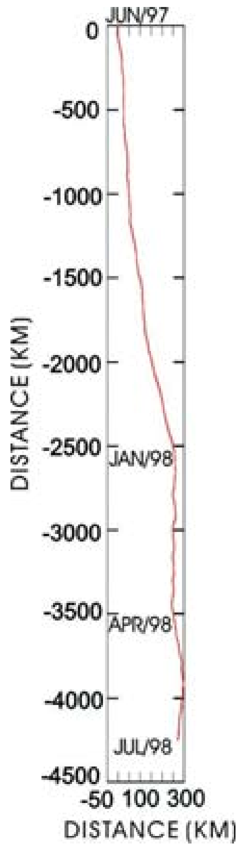


Figure 4. Progressive vector diagram of bottom current at A13.

The late 90s was a period during which the intensification and densification of the outflow of the Cretan Dense Water through the Cretan Straits, that started in the late 80s and peaked in the mid 90s (1995) and at that time was dense enough to occupy the bottom layers of the East Mediterranean, was further weakening (Roether *et al.*, 1995; Theocharis *et al.*, 1999; Kontoyiannis *et al.*, 2005; Theocharis *et al.*, 2002). Figure 3 shows hydrographic profiles at station A13, at the west Cretan Straits in January 1998. There is bottom layer of Cretan Dense Water extending from ~650 m down to the bottom at ~800 that is characterized by higher density, temperature, salinity and oxygen. This dense water mass is outflowing from the Cretan Sea towards the south on the bottom of the outflow channel. Figure 4, which is a progressive vector diagram of the bottom current at A13 for the period June 1997-July 1998, shows this bottom outflow. According to Figure 4, the progressive vector displacements of the bottom current are directed to the south (~170°-180°) and travel a total distance of approximately 4600 km in about 13 months, which implies a mean current speed of ~15 cm/sec. This is a substantial bottom flow. Stronger bottom currents reaching ~40 cm/sec were observed in the mid 90s (1994-1995) in the outflow channels to the east of Crete at the Kassos Strait (Kontoyiannis, 1999).

b. Hydrography, currents and sediment-trap mass fluxes in 2005-2006

Figure 5 shows the hydrographic profiles within the Samaria canyon at station C48 in May 2005. The salinity maximum (~39.3) between 100-200 m is the Levantine Intermediate Water (LIW) that is also accompanied by a local oxygen maximum. The oxygen minimum recorded at ~600 m is due to the Transitional Mediterranean Water (TMW). A weak and broad maximum in the salinity profile between ~1400-2000 m is due to the contributions from Cretan Dense Water (CDW) outflows in the years after the early 2000s (Theocharis *et al.*, 2002; Kontoyiannis *et al.*, 2005). In those years the CDW was not dense enough to reach the bottom of the eastern Mediterranean, but in the vicinity of the Cretan Straits it was spreading in layers between ~1000 m and ~2500 m.

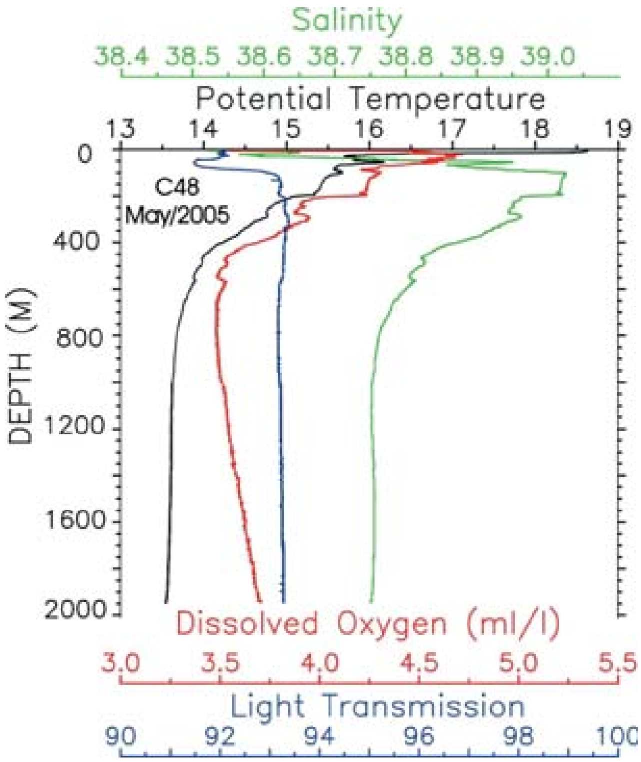


Figure 5. Profiles of salinity, potential temperature, dissolved oxygen and light transmission at Station C48 in May 2005.

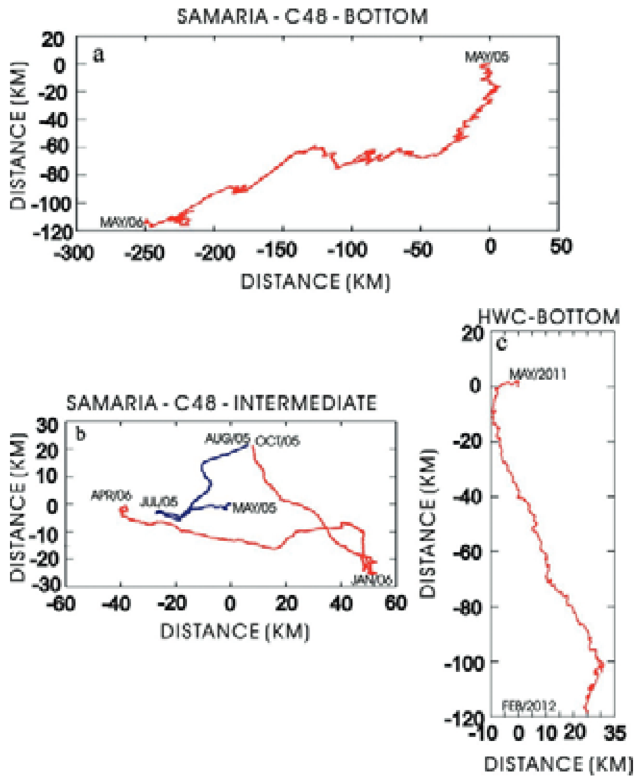


Figure 6. Progressive vector diagrams for the currents at C48 during the period May 2005-May 2006 (panel 'a' for the bottom current at depth 1960 m, and panel 'b' for the current at depth 1000 m) and the bottom current at depth 1500 m at HWC (panel 'c') during the period May 2011-Febrouary 2012. Scales in x-y axes are the same for panels 'b' and 'c', whereas there is a 50% reduction for the x-y scales in panel 'a' relative to 'b' and 'c'.

The current at the bottom of the Samaria Canyon at C48 with a depth of 1960 m is predominantly to the southwest, i.e., along the canyon axis, with a mean speed of ~3 cm/sec (Figure 6). Strong topographic control seems to exist at this position and depth. Higher in the water column at 1000 m at C48, the current however is mostly along a northwest-to-southeast line. This orientation agrees with the general circulation in this area which is, roughly, parallel to the Cretan south coast, i.e., the orientation of the 1000-m depth contour (Figure 2). The mean speed as 1000 m is a little weaker, around 1.8 cm/sec. The speed maxima do not exceed ~14 cm/sec at both depths.

The time series of the lithogenic component of the mass flux at C48 is shown in Figure 7. The lithogenic component is in general more than 50% of the total mass flux.

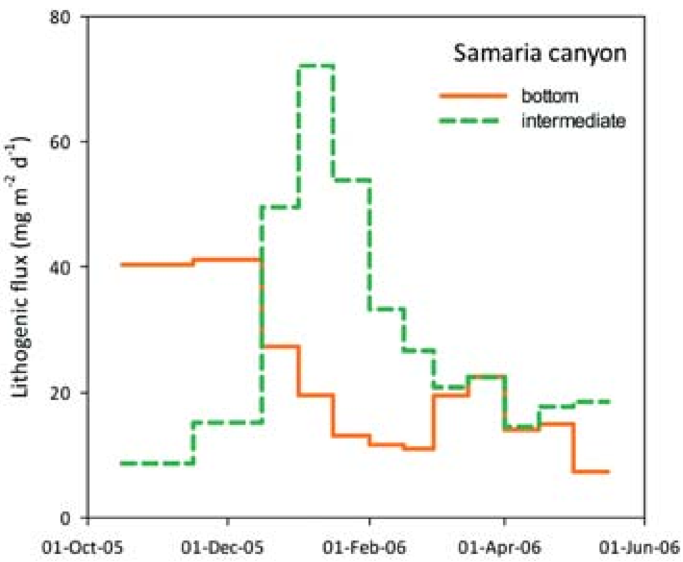


Figure 7. Bottom (1960 m) and intermediate (1000 m) lithogenic flux at station C48 in the Samaria Canyon from October 2005 to June 2006.

The lithogenic mass fluxes are characterized by low values; lower than 100 mg m^{-2} d^{-1}. The bottom fluxes show a continuing decrease, whereas the intermediate fluxes show a local weak peak around January and February 2006. It is possible that winter rainfalls in the same period might have caused lithogenic input at the coastal areas of south Crete and this input may affect the intermediate fluxes at 1000 m as it propagates offshore and sinks.

c. Hydrography, currents and sediment-trap mass fluxes in 2011-2012

Figure 8 shows the hydrographic profiles at station HWC in February 2012, whereas Figure 6 panel ‘c’ shows the progressive vector diagram of the bottom current at the same station. No sharp changes of the hydrologic properties (temperature, salinity, density), which would characterize a bottom plume as in 1998, are detected near the bottom. The bottom current is in generally directed to the south, parallel to the bathymetric contours, but is extremely weak (~ 1-2 cm/sec) and near the threshold detection for most of the deployment period.

Figure 9 shows the record of the lithogenic component of the mass flux at HWC from May 2011 to February 2012. Low-flux values again characterize the lithogenic flux regime in the Antikythera outflow channel. One possibility for the increased values of lithogenic material in late May 2011 is the input from the atmosphere into the Cretan Sea which in periods of predominant southerly winds, such as mid and late spring, is dominated by African dust that is transferred north.

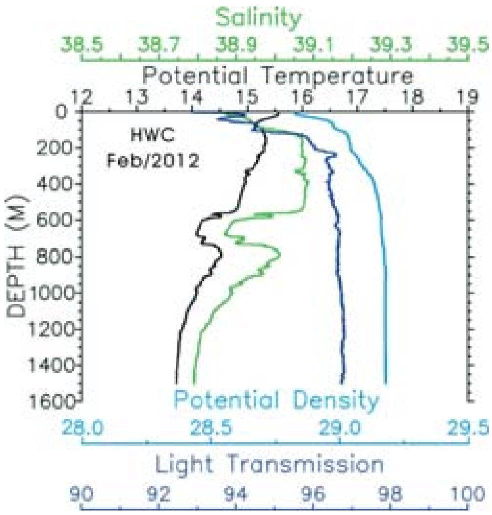


Figure 8. Profiles of salinity, potential temperature, potential density and light transmission at station HWC in February 2012

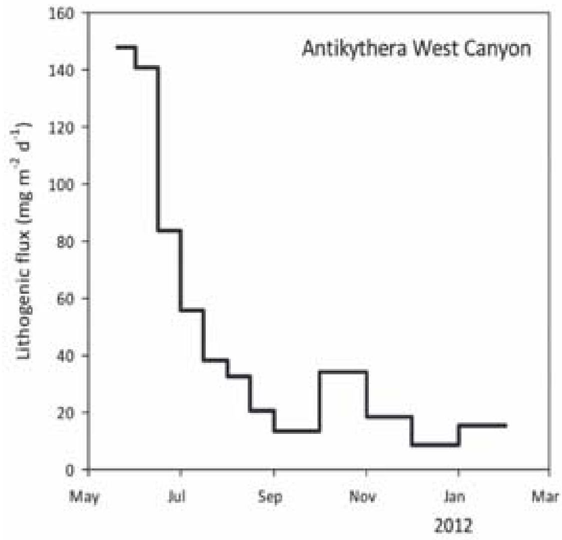


Figure 9. Bottom (1500 m) lithogenic flux at station HWC during the period May 2011 to February 2012.

Summary and conclusions

The complex bottom-terrain of the continental Mediterranean margin to the south of Crete includes deep canyons, such as the Samaria and the Lithinon Canyons that start from the near shore area south of Crete and plunge down into the eastern Mediterranean at depths exceeding 3 km, but also canon-like channels of the Cretan Dense Water outflow that start from the sill area of the Cretan Straits and again descend into the deep east Mediterranean. We provide a brief overview of deep currents and lithogenic sediment fluxes in these bottom geomorphologic features (canyons and deep outflow channels) in the southwestern Cretan margin with yearly-long observations during the periods 1997-1998, 2005-2006 and 2011-2011.

In 1997-1998 the dense water plume on the bottom of the west Cretan outflow channel created a strong southward bottom current (mean speed ~15 cm/sec). In 2005-2006, the bottom flow at 1600 m and the flow at 1000 m in the Samaria Canyon were topographically controlled with weak mean speeds (~2 cm/sec), and the lithogenic fluxes less than 100 mg m^{-2} d^{-1}. There was a possibility for increased lithogenic input from the land in the winter period. In 2011-2012, there was no dense outflow plume in the west Cretan outflow channel. However, the bottom flow was southward along bottom contours but very weak (mean speed ~1-2 cm/sec) while the lithogenic fluxes were lower than 120 mg m^{-2} d^{-1}.

* this chapter is to be cited as:

Kontoyiannis H., Stavrakakis S., Karageorgis A., Lykousis V. 2015. Currents and sediment fluxes in canyons and deep outflow channels at the southwest Cretan margin (Eastern Mediterranean). pp. 137 - 143 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.

Interdisciplinary investigation of off-shelf transport in the southern Adriatic Sea: the role of Bari Canyon

Sandro Carniel[1], Alvise Benetazzo[1], Ferdinando Boero[2,3], Alfredo Boldrin[1], Francesco M. Falcieri[1], Leonardo Langone[4], Mauro Sclavo[1], Marco Taviani[4], Fabio Trincardi[4] and Davide Bonaldo[1]

[1] *CNR-ISMAR, Venezia, Italy*
[2] *Università del Salento, and* [3]*CNR-ISMAR, Genova, Italy*
[4] *CNR-ISMAR, Bologna, Italy*

1. Introduction

Submarine canyons (SC) are submarine valleys with walls of variable steepness, often characterized by tributaries, deeply incising the sea floor of the continental shelf/slope, and mostly continuing seaward (Shepard and Dill, 1966; Hickey, 1995). The submarine canyons of the Mediterranean Sea are more ubiquitous than perceived, where the availability of recent investigation techniques yields more than 500 structures (Harris and Whiteway, 2011; Harris and Macmillan-Lawler, this volume).

Historically, the first motivating reasons of interests for SC exploration trace back to economic reasons, such as exploitation of fossil energy reservoirs or sand deposits, and engineering pipelines deployments; more recently, the scientific community realized that these deep regions play a key-role in ecosystem functioning (Würtz *et al.*, 2012) both for a series of physical, biological, chemical aspects (reflecting on biodiversity, climate change issues and fisheries), and for their role in connecting continental shelves to deep ocean regions as well (and possibly vice-versa).

Indeed these deep incisions within the sea bottom act as tipping-points and natural accelerators, conveying relatively large water masses from “shallow” regions to “deeper” ones in cascading areas, whereas in other areas they are often the trigger of upwellings. In both cases, they reduce the residence time, increase the mixing rates, allow organic and inorganic particles to be flushed and/or resuspended, so enhancing local productivity and boosting food webs.

Although recent efforts have clearly demonstrated the pivotal ecological role of Mediterranean SC, resulting in an increased number of studies (e.g. Della Tommasa *et al.*, 2000; Boero, 2015), much remains to be understood about their functioning mechanisms. Reasons are multiple, among which technical difficulties in operating and obtaining measurements in deep marine regions, different jurisdictions on waters and military use of bottom areas. In addition to this, the intrinsically interdisciplinary approach required to fully understand the complexity and ecological role of submarine canyons has been hampered by a long-lasting reductionist approach, based on the processes division into “scales” (both spatial and temporal).

In the Mediterranean, several large canyon systems are hypothesized to have been formed at the time of a drastic sea-level lowering in the late-Miocene (Messinian), and ensuing refill, while many others, typically smaller in extent, reflect the evolution of continental margin during the Quaternary. In the latter case, global sea level oscillations played a key role in connecting the head region of several canyons to river valleys down-cutting the entire continental shelf at low stands. In such cases, canyons that have been connected to a fluvial feeding systems may have undergone significant processes of down-cutting by turbidity current likely generated through hyperpycnal flows. Many questions about SC remain open (Würtz *et al.*, 2012), related also to their origin (retrogressive failure indenting the shelf edge, erosion by turbidity currents, subaerial erosion of the upper canyon, sidewall erosion related to sediment movement down the canyon). In certain Mediterranean settings, the role of erosive cascades of density bottom-hugged currents originated on the shelf and capable to flush a canyon mimicking a low density turbidity current flow is becoming evident (Malanotte-Rizzoli *et al.*, 2014). This is the case of most canyon systems located on North Mediterranean slopes (Gulf of Lion, Ligurian Sea, Aegean Sea; e.g. Canals *et al.*, 2006). While these canyon settings are impacted by the flow of cold water during major Cold Air Outbreak events from northerly winds, the south Adriatic slope is impacted by a similar atmospheric process but more indirectly and with a significant buffering effect induced by the orientation and extent of its broad shelf region.

We use the Southern Adriatic Sea as an ideal study area for investigating some of these open questions, suggesting a possible multi-disciplinary approach in order to shed some light on processes such as: the interaction between open-slope and canyon dense water downflows, the canyons' role in triggering upwelling currents in a circulation cell (that may lead not only to off-shore, but also to on-shore fluxes, with paramount ecological implications, Hickey, 1995; Canepa *et al.*, 2014; Boero, 2015); the interaction with the bottom boundary layer and the canyons' role as bottom shapers; their relationship with meteoceanic events taking place on the continental shelf.

2. Measurements and modelling approaches in the Southern Adriatic

The Adriatic Sea is a semi-enclosed, basin in the Northern Mediterranean Sea (see Figure 1, left panel), elongated in the NW-SE direction. Its northern sub-basin, gently-sloping and nearly 50 m deep on average, spans from the gulf of Venice to south of Ancona, providing a broad basin for North Adriatic Dense Water (NAdDW) formation by surface cooling under the effect of dominant cold northeasterly winds. South of Ancona, the bottom depth drops from 150 to 280 m below the mean sea level in the Jabuka pit.

The shelf eventually breaks off the Apulian and Albanian coast, dipping into the Southern Adriatic Pit, 1200 m below the mean sea level. The SAP is connected to the Jabuka Pit by the Palagruza Sill in the North, and to the deeper Ionian Sea by the Otranto Sill in the South. As an interface between the Mediterranean and an epicontinental basin acting as a cold engine for regional circulation, the Southern Adriatic Margin is thus a crossroads for a variety of hydrodynamic, geological and biological processes.

During the last decade, observational investigations of dense water dynamics in the Southern Adriatic Margin underwent a change in strategy in the wake of two major elements.

On the one hand the appearance of the first large-scale seabed mapping at an unprecedented degree of detail, obtained by the joint use of traditional sampling techniques and new technologies such as multi-beam echo-sounding (Ridente *et al.*, 2007; Trincardi *et al.*, 2007), allowed to identify patterns of geomorphological features indicating the occurrence of partially recognizable hydrodynamic regimes (Verdicchio and Trincardi, 2006). On the other hand, the advent of relatively high-resolution modelling at basin scale (Carniel *et al.*, 2009), made possible by increasing computational capabilities, allowed a more detailed description of Dense Water (DW) preferential migration and cascading paths and their spatial scales. These factors, together with the increasing awareness of the strong space and time variability of DW dynamics, progressively drove the measurement approach towards a long-term, high-frequency strategy relying on the deployment of fixed moored instrumental chains on some key zones of the continental margin.

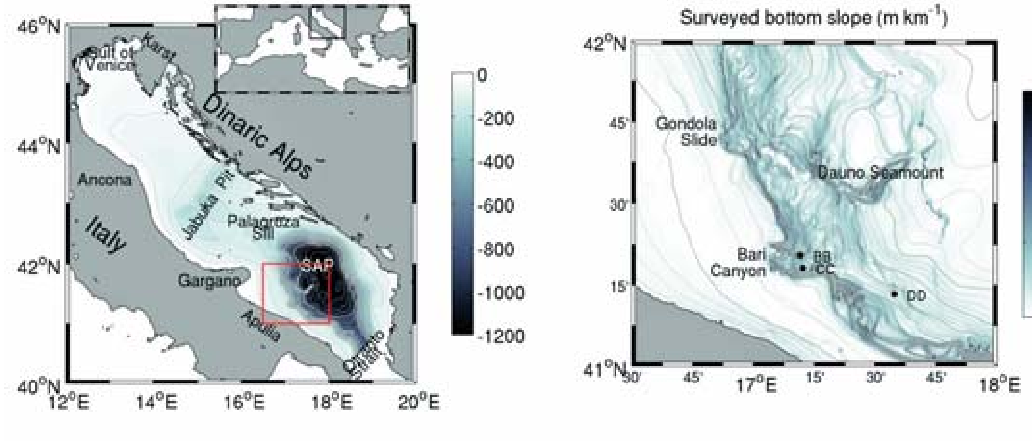


Figure 1. Adriatic Sea (left panel) and detail of the Southern Adriatic Margin (right panel) showing the bottom slope. Moorings name and main locations discussed in the text are also indicated.

These were identified based on geological and modelling clues of DW activity, and such point observations were flanked by a set of traditional (e.g. CTD, XBT, L-ADCP) and non-traditional (Seismic Oceanography, Micro-structure turbulence profiling) measurements carried out during oceanographic cruises for providing a spatial picture of nearly-instantaneous information.

After earlier works (e.g., Bignami *et al.*, 1990; Vilibić and Orlic, 2002), an extensive, interdisciplinary data set was collected on the Southern Adriatic Margin and on the Bari canyon in particular during the last decade, in the framework of a number of national and international efforts, such as EuroSTRATAFORM Project (Ridente *et al.*, 2007; Trincardi *et al.*, 2007; Turchetto *et al.*, 2007) or ADRIASEISMIC Oceanographic cruise (Carniel *et al.*, 2012).

Together with temperature, salinity and current velocity, suspended sediment samples were collected at three mooring sites on the main branches of the Bari canyon and the neighbouring open slope north of the conduits from March 2004 to April 2005 (Turchetto *et al.*, 2007). A longer campaign was set up from March 2009, again on the two channels of the Bari canyon but with a third mooring deployed down-slope and south of the canyon.

An exceptional cooling episode occurred in winter 2012, providing a paramount opportunity for investigating DW dynamics: to this end, two dedicated rapid environmental assessment campaigns named Operation Dense Water (ODW 2012) were carried out from late March to late April 2012, and characterized by a model-driven sampling strategy.

The large amount of data collected during the ODW 2012 campaign and the mooring activity, together with those recorded in the Northern Adriatic especially during the 2012 Cold Air Outbreak event (Mihanovic *et al.*, 2013), provided a sound validation set for a variety of numerical model experiments aiming at a broad characterization of NAdDW dynamics and their drivers.

NAdDW formation, spreading and cascading have been modelled by means of the COAWST (Coupled Ocean, Atmosphere, Wave, Sediment Transport) System (Warner *et al.*, 2010), coupling a fully 3-D, primitive equations, hydrodynamic model (Regional Ocean Modeling System, see Shchepetkin and Mcwilliams, 2005), a phase-averaged spectral wave model (Simulating Waves Nearshore, see Booij *et al.*, 1999) and a sediment transport module (Community Sediment Transport Modeling System, see Warner *et al.*, 2008). The system was implemented with reference to the period November 01, 2011 to June 30, 2012, over an eddy-permitting regular grid with 1 km horizontal resolution, and vertically subdivided into 30 terrain-following levels, stretched in order to achieve improved resolution close to the surface (for better describing cooling and densification processes) and close to the bottom (aiming to capture vertical variability within the bottom-hugging DW vein). While a complete description of the model settings can be found in the works by Benetazzo *et al.* (2014) and Carniel *et al.* (2015a), it is worthwhile recalling here that the set of implementations was characterized by different combination of forcing factors such as tides, riverine input, sediments and waves, selectively activated or deactivated in order to investigate their effects on DW dynamics and their interrelations.

3. Observations in the Adriatic - Bari canyon and South Adriatic Margin

3.1 Geomorphological setting

The Southern Adriatic Margin (see Figure 1) was shaped during the last half million years over a tectonic structure of Mesozoic carbonate platforms controlling lateral variability in shelf width and dip gradients (De' Dominicis and Mazzoldi, 1987). Local margin tilts and deformations are nevertheless controlled by patterns of Pleistocene regressive frequencies, where mass wasting and slope failure gave rise to deep incisions on the shelf edge. The progressive evolution of these scars towards a canyon configuration (such as in the case of Bari canyon, Figure 2) or a slide-deposit form (Gondola slide, see again Figure 1, right panel) depended on the frequency of failure and the location of the head with respect to the shore, controlling the capability of capturing dense bottom currents during both highstand (dense shelf water cascading) or lowstand (sediment-driven turbidity currents, see Ridente *et al.*, 2007).

Thus the present structure of the Bari canyon system (Figure 2), approximately 10 km wide and extending offshore for 30 km, consists of three sub-parallel conduits carving the continental slope in the W-E direction. The northernmost conduit, referred as Moat A (Trincardi *et al.*, 2007) is sinuous, slope-confined, downslope-broadening, and displays erosional features on its northern flank and likely muddy deposits on the southern one. South of Moat A, two shelf-indenting channels develop with a significant cross-slope variability in morphology and gradient. Adjacent to Moat A, Channel B appears straight, confined and erosional in the upper slope (down to 620 m), narrower and sinuous down to 750 m and eventually more defined until disappearing in water depths greater than 1100 m (Trincardi *et al.*, 2007). The southernmost conduit, identified as Channel C, is broader, straight and asymmetric, being separated from Channel B by a gently-sloping (0.6°) mounded relief in the north and flanked by a steep southern wall in the south (Ridente *et al.*, 2007).

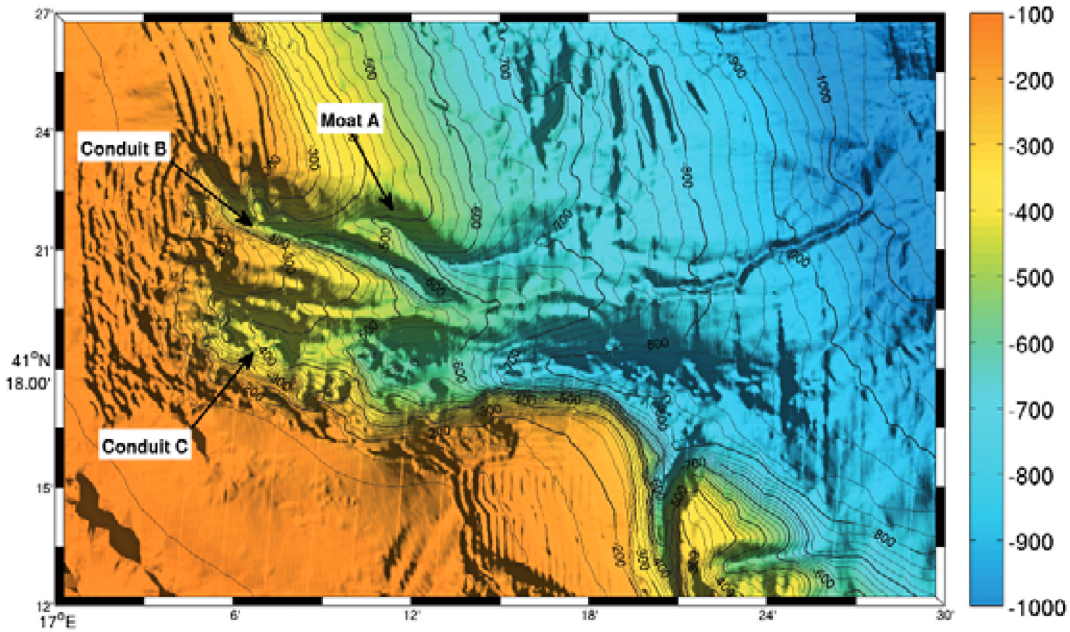


Figure 2. Detailed bathymetry of the Bari canyon system (m).

At a smaller scale, the Bari canyon system exhibits (see again Figure 2) the marks of a complex morphodynamic activity, involving the conduits and the neighbouring slope. Seismic profiles show a lateral spreading of the southern levee of channel B towards conduit C, consistently with flows predominantly overbanking to the right of the conduit (Trincardi *et al.*, 2007). Furthermore, erosional features in the median relief between B and C suggest the presence of energetic mass exchanges from the northern to the southern channel (Ridente *et al.*, 2007). Along the southern wall of canyon C, approximately 700-850 m deep, furrows have been observed, prevailingly oriented along-axis and progressively right-veering downslope (Verdicchio *et al.*, 2007). About 10 km seaward, at a depth ranging between 800 and 950 m, sediment undulations oriented in the NNE-SSW direction and with wavelength of 700-1300 m have been described by Trincardi *et al.* (2007) and Foglini *et al.* (2015), where mooring DD was positioned.

Interestingly, even south of the Bari canyon the continental margin towards the Otranto strait appears marked by highly-energetic, nearly contour-parallel currents (Foglini *et al.*, 2015), with extensive erosional fields along the slope change and a transverse scouring involving a canyon system, formerly delivering coastal sediment to the deep basin during the Last Glacial Maximum and now relict and partially disconnected from the shelf.

In fact, a manifold pattern of erosional and depositional bedforms indicative of a strongly space- and time-variable hydrodynamic regime (Verdicchio and Trincardi, 2006) studs the whole South Adriatic Margin. Their metrics and disposition, made readable by new techniques of multi-beam echosounding combined with stratigraphic chirp data (Foglini *et al.*, 2015), mark on a broader scale the activity of interacting bottom currents at the edge of this reach of the continental shelf.

3.2 Hydrology

Thermohaline properties on the continental margin exhibits seasonal modulation, with (potential) temperature at near bottom ranging overall between 12.20 (Langone *et al.*, 2015) and 14.42 °C (Turchetto *et al.*, 2007), with a maximum typically occurring in December and a minimum in March-April. Salinity in turn spans a narrower range (38.62-38.74 during Spring 2012 event, see Langone *et al.*, 2015). Hydrodynamic regime displays a strongly variable bottom current intensity throughout both the open slope and the canyon conduits, with pulses up to 0.60 m/s and 0.75 m/s respectively, corresponding to cold, dense shelf waters transit. 2004-2005 EuroSTRATAFORM dataset reports a nearly constant current direction in the open slope north of Bari canyon, oriented on average along the regional isobaths and with a few degrees downslope veering in presence of stronger speed (>0.30 m/s) episodes (Turchetto *et al.*, 2007). Positions of active moorings are presented in Figure 1 (right panel). Observed potential density at moorings BB, CC, DD, registered during ODW 2012 campaigns are shown in Figure 3.

Current directionality in the canyon proper exhibits instead a more variegate behaviour. Both the available datasets (2004-2005, see Turchetto *et al.*, 2007 and Rubino *et al.*, 2007; and 2009-2012, see Langone *et al.*, 2015) highlight in BB a clustering along two directions (see Figure 3), one oriented southward along the regional contours, and one oriented downslope along the conduit axis Whilst the former is dominant during most of the year, the latter is especially active in spring, corresponding with dense water arrival. Dense water downflow takes place along both directions (Turchetto *et al.*, 2007), but with a fundamental difference in water properties; indeed, as along the conduit the NAdDW cascading signature is most clear in terms of both velocity and thermohaline properties, in the slope-parallel direction only the kinetic signal is strong, while the density signature is only partially retained. Lower velocity (less than 0.20 m/s) concomitant with smaller density anomaly (below 29.2 kg/m3) can be interpreted as a signature of the background circulation, exhibiting thermohaline properties that can be ascribed to the Modified Intermediate Levantine Water (Carniel *et al.*, 2015).

In turn, the steep southern wall of conduit C acts as a major constraint for the flow along the canyon axis towards the off-shelf direction, practically independent of the physical properties of the water mass.

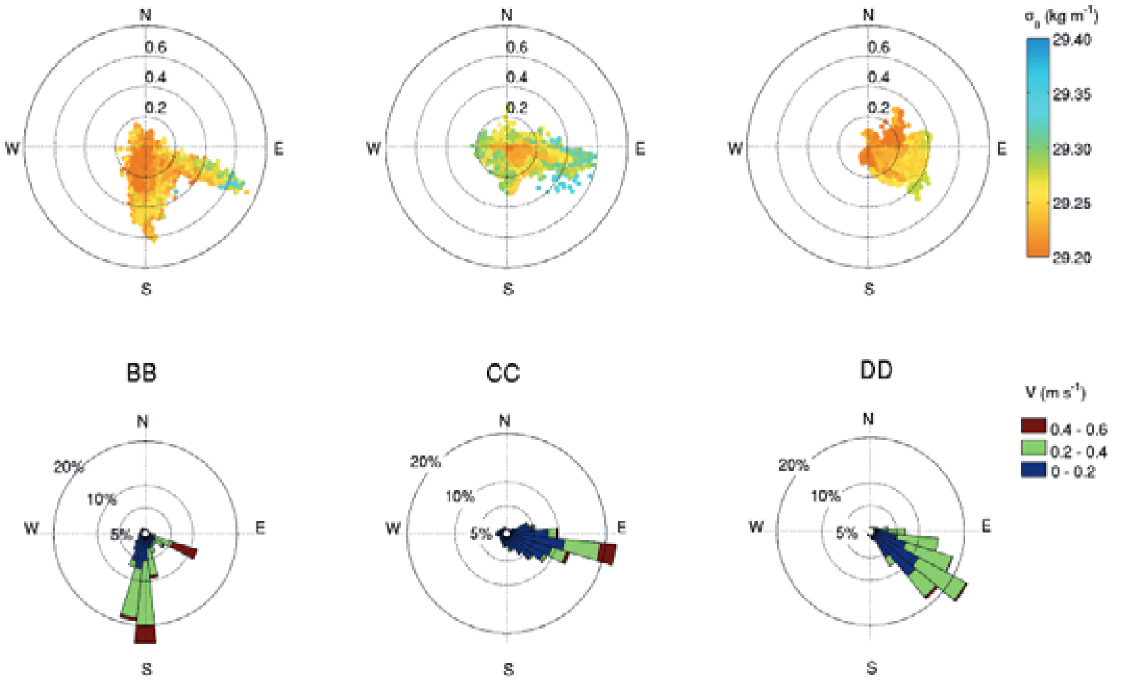


Figure 3. Upper panels: observed directional current velocity (m s^{-1}) and potential density (kg m^{-3}) at moorings BB, CC, DD (see Figure 1, right panel). Lower panels: occurrence probability of observed current velocity (m s^{-1}) clustered every 0.2 m s^{-1}. Data were obtained during ODW 2012 campaigns.

Together with a physical characterization of water masses transiting through this sector of the continental margin, the availability of yearly or longer observational records allows the identification of timing and modulation of dense water descent on the conduits of the Bari canyon. Several studies (e.g. Vilibic and Orlic, 2002; Rubino *et al.*, 2012) identify in 2-4 months the period needed for NAdDW to propagate from the generation basin to the Southern Adriatic region. On the other hand, during winter-spring 2012 episode, high-frequency cold and low-salinity water pulses have been observed on the continental margin since mid February, only two weeks after the Cold Air Outbreak inception, with negative shift in temperature on the order of 0.35 – 0.60 °C. Subsequent intrusions of cold water were recorded until June, with variable characteristics along the continental margin (Langone *et al.*, 2015).

Besides traditional measuring strategies, new advances toward nearly-synoptic observation of large-scale patterns of dense water spreading along the continental margin are made possible by seismic oceanographic techniques (Holbrook *et al.*, 2003). By using the techniques primarily designed to image sub-seafloor geologic structures, it was recently shown that it is possible to provide images of water layers in the ocean, since the lower frequency sound waves used (from about 10 to 200 Hz) are coherently reflected directly by the thermohaline boundaries between water masses on the scale of meters to tens of meters (Ruddick *et al.,* 2008). Such acoustic measurements were integrated with eXpendable Bathy-Thermographs (XBTs) or Conductivity-Temperature-Depth (CTD) casts during the international ADRIASEISMIC cruise (March 3-16, 2009), carried out on board the CNR R/V *Urania* in the southern Adriatic Sea. It was the first experiment in seismic oceanography that specifically targeted structures in shallow waters (along the western margin of the Adriatic Sea between the Gargano promontory and the Bari canyon, see Figure 1).

3.3 Sediment transport and biological/biogeochemical aspects

The export rate of organic carbon provides a proxy for the efficiency of the biological pump in delivering mass, produced by phytoplankton in the photic layer, into the deep ocean (Boldrin *et al.*, 2011) and Bari canyon is considered to play an important role in the sediment transport dynamics in the southern Adriatic basin, representing an efficient conduit in delivering suspended sediment from the continental shelf to the deep basin (Turchetto *et al.*, 2007). In this, long-term sampling via time-series sediment traps allows a characterization of timing and biogeochemical composition of sediment transiting in the measurement zone.

A set of sediment traps moored along the continental margin, together with current meters and other instruments, provided background for a number of inferences and, particularly, important information about cross-shelf sediment transport. Turchetto *et al.* (2007) showed that, although dense water downflow processes involve also the open slope, the Bari canyon acts as a main pathway for off-shelf sediment fluxes, and highlighting that the DSW cascading is responsible for the higher particle delivery both in the open slope and canyon stations. Monitoring efforts in the Bari canyon highlighted that the main organic carbon source is constituted by vertical sinking of marine phyto-detritus, ranging from ~60% during dense water cascading, up to 90% during low energy conditions (Tesi *et al.*, 2008), the remaining part constituted by horizontally-advected kerogen and soil-derived organic carbon in almost similar proportions.

Superficial sediment sampling on the continental shelf and on the slope allows the identification of the origin of laterally-advected particles. Tesi *et al.* (2008) assessed the origin of exported sediment, highlighting that the direct transport of material from river mouths and inshore region is practically excluded in present highstand conditions and therefore that the downflowing matter is mostly resuspended on the slope and outer shelf. In contrast, Langone *et al.* (2015) concluded that during the 2012 DSW cascading events particles in transit in the water column had a larger contribution of fresh organic matter resulted from enhanced productivity, which was quickly transferred from surface waters of Northern Adriatic shelf to the bottom of Southern Adriatic. Overall, DSW cascading acts as a primary control on the particulate fluxes through the western margin of the Southern Adriatic, whereas storm-induced sediment transport can play a secondary role (Langone *et al.*, 2015).

Due to the prolonged flushing of sea bottom during DSW cascading and the low but relatively constant organic carbon supply during the rest of the year, the Bari canyon appears to be a suitable area to be colonized by sessile deep-sea benthic communities (e.g., cold-water corals).

Conspicuous megafaunal sessile communities, including cold-water and sponge habitats, show an asymmetric distribution in the southern Adriatic with most diverse and abundant live corals settling on the western side, especially the Bari canyon (Taviani *et al.*, 2015). This observation has been hypothesized to be at least partly a response to the seasonal action of dense shelf water cascading flushing the canyon and adjacent areas by limiting excess silting and favouring the food web (Taviani *et al.*, 2015).

This brief summary provides an account of the wealthy set of traditional and new-generation observational data currently available on the Southern Adriatic Margin, and in particular on the Bari canyon system. In this picture, a number of questions should be framed into a multi-disciplinary context arise. What are the interactions between dense shelf water cascading and large-scale circulation in the Bari canyon and what is, in integral terms, the relative weight of open-slope and canyon cascading in NAdDW descent? How does this relate to the hydrological and geological patterns observed (or conjectured) in this zone? What is its relationship with the forcing factors driving water cooling in the Northern basin? Vice versa to what extent does canyon-induced upwelling recirculate deep sea matter towards the continental shelf, and in general what are the mechanisms and connections by which Mediterranean circulation and large-scale atmospheric patterns control cross-shelf mass transport?

4. Model results

Although near-bottom currents in the Bari canyon region were recently explored by Rubino *et al.* (2012) by means of a reduced-gravity numerical model, the extent of some conclusions was admittedly limited by the coarse bathymetry resolution and the impossibility of accounting for the effect of air-sea interactions and ocean dynamics at regional scale.

Benetazzo *et al.* (2014) addressed these questions by investigating the process dynamics using a coupled numerical model approach and adopting a high-resolution description of the bathymetric forcing, modeling the whole Adriatic basin under the effect of a number of variable drivers. In this direction, a comprehensive description of dense shelf water formation and spreading processes was stimulated by the exceptional Cold Air Outbreak event of 2012 and the ODW dataset, that also provided a striking examples of how deep basin dynamics (including those characterizing the Bari canyon system) can be intrinsically linked with shelf processes

From 29 January to 13 February 2012 the Northern Adriatic basin was hit by a Cold Air Outbreak with strong, cold and persistent winds blowing from SE across the Karst and the Dinaric Alps, with a prolonged establishment of large significant wave height (more than 2 metres), current velocity (up to 1 m s^{-1}) and turbulent heat fluxes at the air-sea interface (up to 800 Wm^{-2}, see Mihanovic *et al.*, 2013). As a response, a steady circulation pattern appeared, with a cyclonic gyre in the gulf of Venice and an intense meridional stream from the Kvarner gulf towards the Italian coast and then southwards along the shelf contours, partially recirculating north of Ancona.

The southernmost front of the very dense water originated in the northern basin (up to record-breaking value of 30.30 kg m^{-3}) left the generation basin, reaching the southern basin before the end of the Cold Air Outbreak. In subsequent weeks, dense water vein migrated southwards parting into two branches south of Ancona: hence, the fraction flowing along the deepest reaches of the shelf was partially deviated towards the Jabuka Pit before proceeding towards the Southern Adriatic Pit across the Palagruza Sill, whilst the shallower fraction maintained its nearly-coastal route, exhibiting a meandering behaviour especially south of the Gargano promontory, compatible with the pulses observed at the mooring stations by Langone *et al.* (2015), with a PDA greater than 29.2 kg m^{-3}, and with the propagation of topographic waves along and off the continental shelf (Carniel *et al.*, 2015a).

Dense water cascading, initially occurring as intermittent pulses, becomes progressively more regular as the process becomes dominated by the buoyancy difference and as the memory of the kinetic energy injection during the Cold Air Outbreak is lost. At the end of April the South Adriatic Pit appears completely renewed, with the 29.2 kg m^{-3} isopycnal set about 900 m deep and a cyclonic circulation established along the lower slope. With the depletion of the generation basin in May, the cascading intensity progressively decreases up to eventually ceasing in June.

Figure 4 shows some modeling results (for a complete model validation see Carniel *et al.*, 2015a; Bonaldo *et al.*, 2015), such as the vertically integrated water and sediment fluxes along the western margin within the period 01 February – 31 May, 2012. Although most of the western slope is hit by dense water cascading, in the Bari canyon water and sediment transport occur with special intensity and with a strong spatial variability. Vertically averaged velocity on the NAdDW vein (Figure 4, left bottom panels) and mean acceleration patterns of bottom currents (right) are also shown.

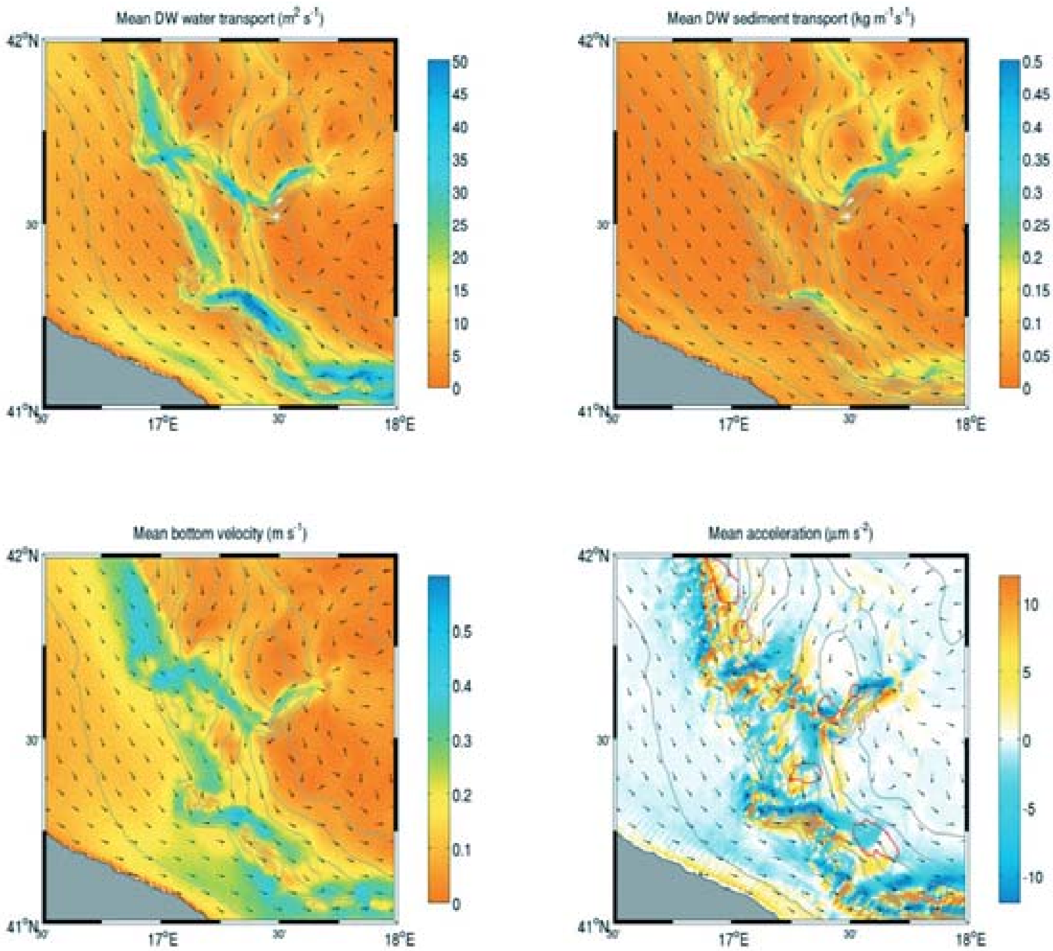


Figure 4. Modelled features of the NAdDW vein in the Southern Adriatic, averaged within the period February 01 to May 31, 2012.
Upper panels: vertically-integrated water (left) and sediment (right) fluxes within the dense water vein.
Lower panels: bottom velocity (left) and acceleration patterns of bottom currents (right). Red polygons represent erosional (dashed) and depositional (solid) fields (see Foglini *et al.*, 2015).

Bonaldo *et al.* (2015) showed that modelled flow field provides a good instrument for understanding the mechanisms responsible for bottom reshaping along the continental margin. In particular, acceleration and deceleration pattern proved to match rather well with observed erosional and depositional features (see again Figure 4, right bottom panel), while the analysis of modelled time series allowed to identify the suitable conditions for the appearance of the considered bedforms. Focusing on the Bari canyon system, it was found that the Flood criterion (Flood, 1988) for mudwave maintenance is fulfilled on the depositional zone north of channel A throughout most of the considered period, but the sediment supply necessary for their accretion is provided by dense water downflow from the northern reaches of the continental slope. In turn, downslope the steep southern flank Conduit C, current velocities are compatible with sediment deposition, whereas strong, directionally stable speed occurring during the Feb-May period are capable of inducing furrows formation (Stow *et al.*, 2009). It is worth pointing out that strong current speed (up to 0.50 m s^{-1}) occurs during February 2012 but before the arrival of the NAdDW vein, suggesting that this zone is ordinarily active under the effect of strong coastal storms characterized by local cooling. Current speed frequently exceeding 0.30 m s^{-1} in the February-April period can give rise to the erosional features observed in the downslope flank of the waves by Foglini *et al.* (2015).

An intercomparison among the results of our set of numerical experiments allowed to identify the role played by various forcing factors in controlling dense shelf water formation and spreading.

Although the general pattern of DSW dynamics (formation north of Ancona, presence of a northern gyre and a zonal current, splitting into a "coastal" and a "Palagruza" stream modulated by the transit in the Jabuka pit, downflow distributed along the western margin) is a common aspect for all implementations considered, major implications from variations in model settings and forcings concern timing, dense shelf water volume and thermohaline and dynamic properties, and distribution between the coastal and deep streams.

Benetazzo *et al.* (2014) pointed out the role of wave coupling in modulating heat and momentum transfer from the atmosphere into the water column and the relevance of explicitly computing the intensity of Stokes currents. In the absence of these factors, surface currents in the northern basin are reduced by about 20% the average current speed and heat fluxes are reduced by 10%. This results in a different estimate of overall dense water volume approaching the SA (3160 km^3 vs 2075 km^3, Carniel *et al.*, 2015b). Furthermore, potential vorticity conservation implies that a dense water vein leaving the generation basin at a higher speed establishes at a shallower depth, favouring the coastal path and the eventual passage through the Otranto Strait on the continental shelf rather than across the Otranto Sill (Carniel *et al.*, 2015a). Tides as well have been found effective in modulating instantaneous dense water fluxes (Benetazzo *et al.*, 2014), urging a deeper exploration of the role of the tidal forcing in driving dense water dynamics. Although autumn 2011 was not characterised by exceptional riverine freshwater input, Carniel *et al.* (2015) estimated that this factor accounts for approximately 30% difference of dense water production.

The same authors evaluated the effect of the presence of suspended sediment along the water column, suggesting that in the absence of a substantial influence on the overall fluxes, the effect of density (and horizontal density gradients) on the spatial distribution can concentrate part of the vein towards the deeper zones, enhancing Jabuka pit renewal and the "Palagruza" stream.

To complete the picture, other works (Carniel *et al.*, 2015b) showed how interface processes can modulate ocean circulation and cooling and condition the pathways of newly dense water up to its eventual cascading into the Southern Adriatic Pit.

Further they highlighted two recurrent features of dense water downflow, namely the relevance of open-slope in the overall off-shelf fluxes and the role of shelf break morphology in selectively triggering cascading processes. Based on the same model results described by Benetazzo *et al.* (2014), Bonaldo *et al.* (2015) point out the role of the topographic constraint in driving DW cascading under the dynamic effect of shelf indentations and variations in seabed slope and curvature.

5. Discussion and conclusions

Submarine canyons are key-regions playing a relevant ecological role in connecting the shelf regions to the deeper ones, where *in situ* measurements are very difficult to be collected and long-term series are very scarce. Therefore, a good practice to employ when studying these underwater conduits is to follow an integrated use of available data and high-resolution numerical modelling. This approach is valuable for capturing dense water dynamics variability in space and time, and for interpreting available measurements in terms of interacting processes at different scales (Rubino *et al.*, 2012). Lessons learned from the activities carried out in the Southern Adriatic during the last decade represent a sound background for the analysis of canyon dynamics and their relation with open-slope processes in a broader framework. A similar approach has been also proposed by Fabri *et al.* (this volume), as support to "habitat mapping" procedures.

In the specific case of the Bari canyon system, the collection of long-term series of continuous temperature, salinity and current velocity data at near-bottom layer in the main conduits provides a comprehensive picture of current regime and thermohaline properties, their modulation in time and interannual variability (Langone *et al.*, 2015). Suspended sediment sampling by means of automatic sediment traps undergoes well-known limitations related to the low measurement frequency, unavoidable in the case of long deployments, and to the difficulties in reconstructing the transport regime actually responsible for the observed sediment deposition. Some effort towards a continuous, high-frequency suspended sediment transport monitoring strategy would probably pay back with a clearer identification of the drivers and intensity of sediment transport processes, permitting an assessment of their dynamic implications especially during intense events. Nevertheless information provided by sediment traps allowed to draw important inferences about sediment transport seasonal and interannual variability (Turchetto *et al.*, 2007; Langone *et al.*, 2015), their origin (Tesi *et al.*, 2008) and a proxy of its distribution along the continental margin (Langone *et al.*, 2015; Carniel *et al.*, 2015a).

Recent high-resolution, state-of-the-art modelling efforts shed additional light on the processes taking place on the Bari canyon from a continental margin perspective. The extensive data set highlighting the intense processes occurring on the Bari canyon was combined with state-of-the-art model results, showing that dense water downflow in the open slope (experimentally observed albeit with a locally weaker intensity) is responsible for the majority of mass transport towards the Southern Adriatic Pit. In general, while the forcings acting on the dense water mass during its formation and its spreading are crucial in determining the "capture efficiency" of the shelf break (namely, the ratio between total dense water approaching the Southern basin and the cascading fraction), the distribution of downflow along the margin appears controlled by the large-scale shelf morphology. Seabed topography, and especially variations in slope and curvature, then defines preferential pathways for the downflowing streams. In turn, NAdDW descent is a main (but not the unique) cause for the emergence of peculiar patterns of erosional and depositional bedforms with intermediate characteristics between the well-known categories of contourites and turbidites.

Successes and limitations arising from this experience indicate major axes to be addressed in dense water processes and submarine canyon hydrodynamics modelling strategies. Besides the obvious opportunity of having an appropriate horizontal (at least eddy-permitting) and vertical (both close to the surface and close to the bottom) resolution for the computational grid, Bonaldo *et al.* (2015) emphasize the importance of a detailed bathymetric description, with special attention to the trade-off between numerical stability and quality of the topographic information (Haney, 1991). Waves and tides appear as essential ingredients for a comprehensive insight on the processes related to DW formation and propagation. In particular, the paramount importance of air-sea interactions and their modulation by waves highlights the necessity of an integrated, fully coupled modeling approach. The challenge of a model fine-tuning by improved parameterizations and an extensive calibration appears as a staging post in this direction.

More generally, if recently relevant progresses have been achieved in understanding the driving mechanisms and the preferential pathways of continental margin flushing, its on-shelf counterpart is still partly unexplored. Whilst the function of canyons in off-shelf transport may in a way appear diluted by the broader extent of open-slope downflow, their role can gain centrality as funnels for upwelling circulation from the lower slope and abyssal plain to the shallow coastal zone (Hickey, 1995; Connolly and Hickey, 2014; Canepa *et al.* 2014; Boero 2015).

As suggested by some, the effect of these processes in governing the functioning of ecosystems is potentially fundamental. For instance, Canepa *et al.* (2014) point out that beach stranding of *Pelagia noctiluca* jellyfish occurs in greatest concentrations in proximity of submarine canyon heads, leading to hypothesize a seasonal migration strategy along submarine canyons for a number of other species (Boero, 2015), based on fluctuations in temperature and nutrient supply.

If the cold engines of the Mediterranean warrant the deep water renewal at sub-basin level (with the Gulf of Lion acting in the Western Mediterranean, and the Northern Adriatic and Northern Aegean acting in the Eastern Mediterranean) by cascading phenomena that flow through canyons, (the Bari canyon being the route of the Northern Adriatic cold engine), the upwelling generated by canyons might be a further engine system leading to localized vertical mixing. Cascading phenomena are not generated by canyons but use canyons (Malanotte-Rizzoli *et al.*, 2014), whereas upwelling phenomena are often generated by canyons. In this way, the vertical mixing of Mediterranean waters may be due to a combination of both cascading and upwelling phenomena. The impairment of the cold engines (as happened during the Eastern Mediterranean Transient) might be, at least partially, buffered by the synergistic action of a myriad of canyons indenting a the whole Mediterranean slope and generating localized upwellings.

Unwinding the thread of these concepts is a real challenge, as it is evident enough that a coherent view of submarine canyons functioning intersects marine trophic networks, nutrient and carbon exports, fisheries, climate dynamics, towards a global reach that is far beyond the apparently local canyon dynamics.

Acknowledgements

The authors are grateful to RITMARE project (SP3-WP4, SP5-WP3) and the EU funded CoCoNet Project (http://www.coconet-fp7.eu/) for the partial support provided.

---

* this chapter is to be cited as:

Carniel S., Benetazzo A., Boero B., Boldrin A., Falcieri F.M., Langone L., Sclavo M., Taviani M., Trincardi F., Bonaldo D. 2015. Interdisciplinary investigation of off-shelf transport in the southern Adriatic Sea: the role of Bari canyon. pp. 145 - 156 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.

Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea

Silvia Ceramicola[1], Marianne Coste[1,2], Daniel Praeg[1,2], Sébastien Migeon[2] and Massimo Zecchin[1]

[1] *OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy*
[2] *Géoazur, UMR7329, Valbonne, France*

Abstract

The tectonically active Ionian continental margin of Calabria is incised by a dense network of submarine canyons, here investigated using multibeam morpho-bathymetric data integrated with subbottom and seismic profiles. These data indicate that the canyons have formed since the mid-Pleistocene, in response to km-scale uplift of Calabria over the last ca. 1 Ma. Despite their young age, the canyons have incised the continental slopes and (narrow) shelves south and east of Calabria over lengths of tens of kilometers, widths up to 2 km wide, and relief in place greater than 200 m. Some canyons are isolated, others have formed hierarchic systems with five or more canyons merging to build dendritic systems that extend over perimeters of 50 km and may or may not be connected to onshore drainage networks. The canyons are inferred to have developed by a combination of retrogressive (headward) erosion and offshore sediment shedding, driven by rapid differential uplift interacting with glacial-interglacial variations in relative sea level. Many canyon headwalls lie close to or at the coast, and so represent potential geohazards to coastal communities and infrastructures.

Tectonic setting

The Ionian Calabrian margin (ICM) is an accretionary complex that has grown during a rapid southeastward advance over the last 10 Ma in response to rollback of the underlying subduction zone during opening of the Tyrrhenian Sea (Sartori, 2003; Minelli and Faccenna, 2010).

The complex includes the onshore Calabria-Peloritani Block, composed in part of basement rocks dissected by NW-trending shear zones and an offshore accretionary wedge dominated by landward dipping thrusts that extends more than 200 km to the front of the prism at 4500m water depth (Fig. 1). Near the Calabrian coast, older thrusts are overlain by sediments of the Crotone-Spartivento Fore-Arc basins (Fig. 1), up to 3 km thick and dating back to the mid-Miocene. The inner part of the Crotone Basin is exposed on land, the result of km-scale uplift of onshore areas since the mid-Pleistocene, c. 1 Ma (Westaway, 1993), coincident with a reduction or cessation of subduction zone rollback. The margin remains seismically active although no recent large earthquakes (magnitude >5) have been recorded.

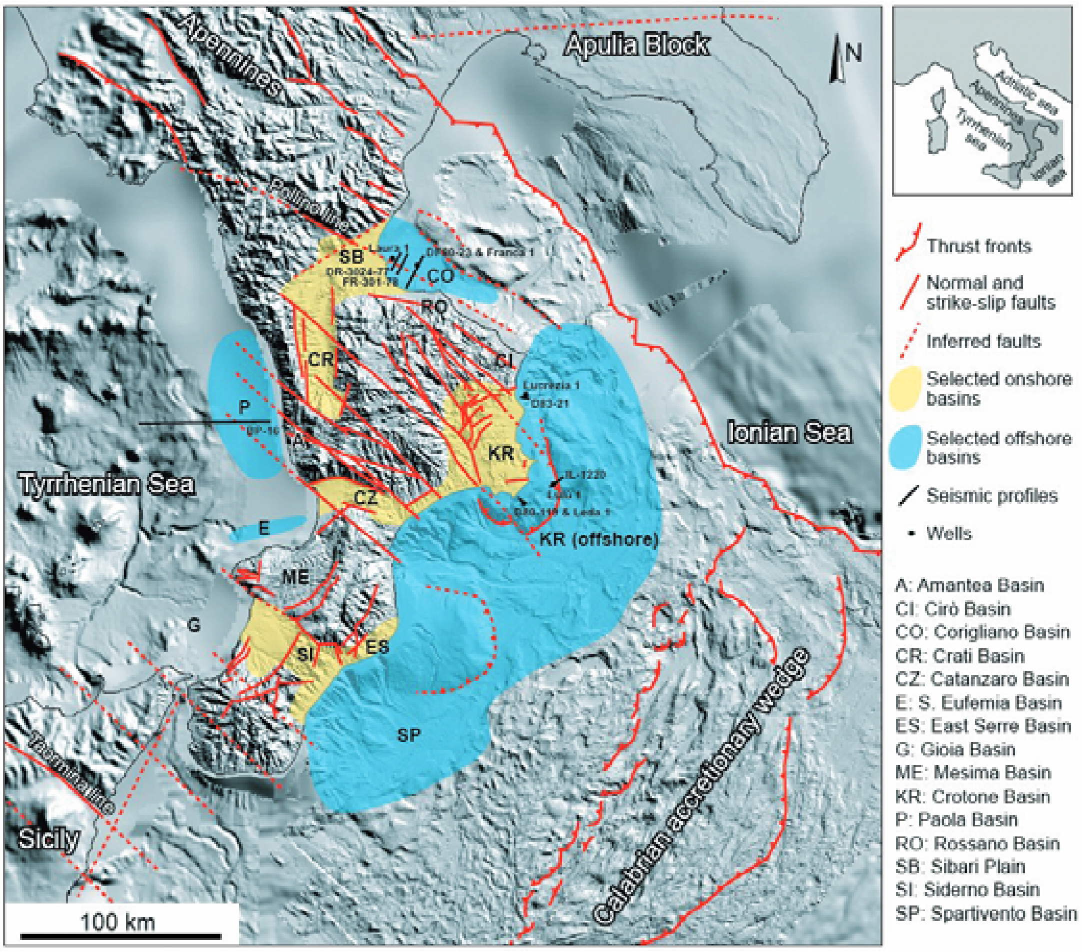


Figure 1. Tectonic setting of the Ionian Calabrian Margin (ICM).

Geomorphological setting

The geomorphology of the Ionian Calabrian margin shows strong differences between northern and southern sectors (Fig. 2). In the northern sector, east of Calabria, the margin is characterised by structural highs and intraslope basins, which represent an offshore extension of the onshore thrust-fold belt of the southern Apennines. Here the continental shelf is broader (2 km) and the irregular continental slope is overall rather gentle (2-5°). In the southern sector, in contrast, the continental shelf is narrow to absent, and the slope dips steeply (5-15°) to the flat floors of the deep-water fore-arc basins (Ceramicola *et al.*, 2014).

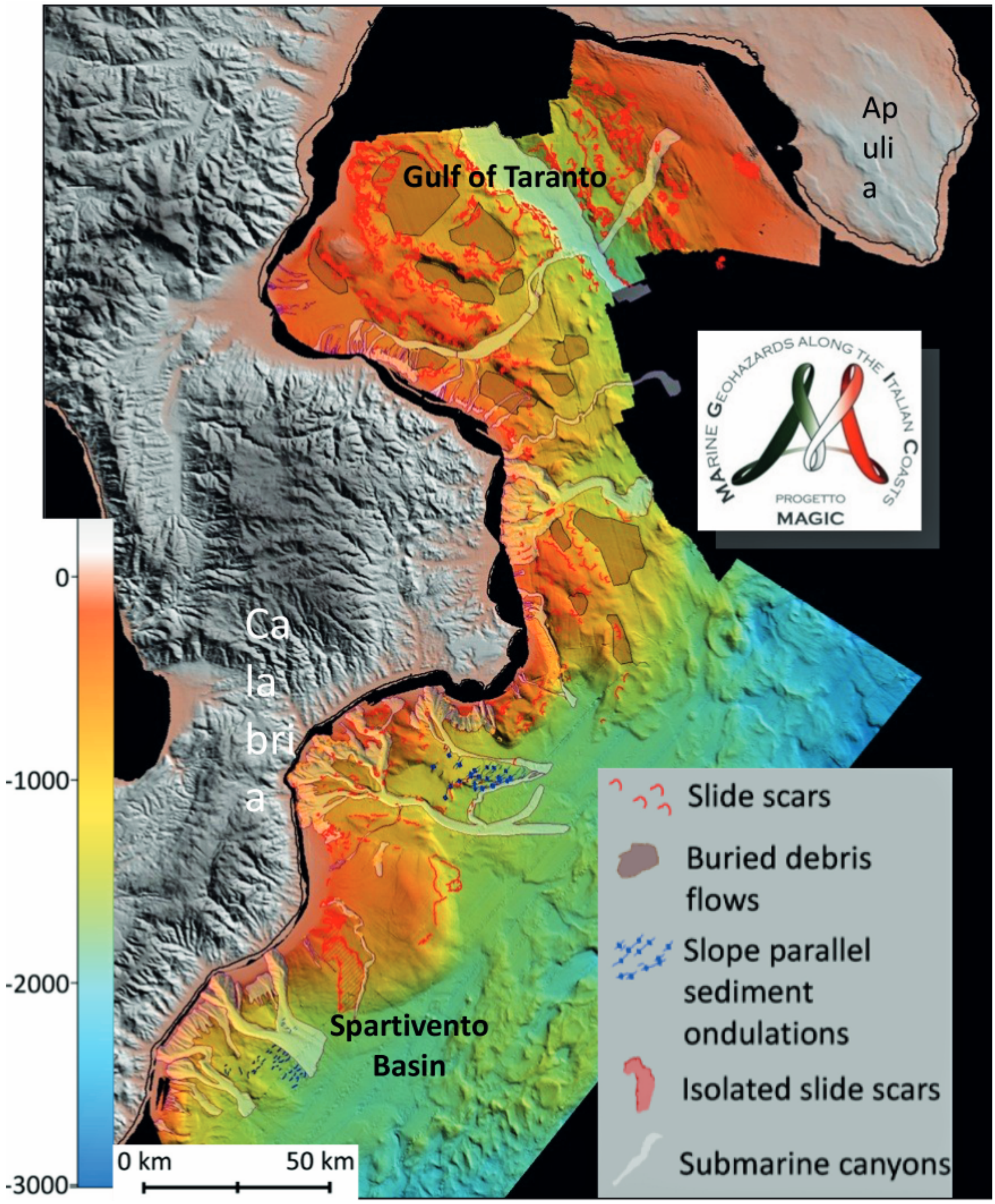


Figure 2. Morphological setting of the Ionian Calabrian Margin (ICM).

SUBMARINE CANYONS

Recent investigations in the framework of the MAGIC project (Marine Geohazards Along the Italian Coasts), funded by the Italian Civil Protection agency, have revealed a dense network of canyons with different morphology and organization along the ICM. The nature and dynamics of the canyons have been studied through seabed mapping using morpho-bathymetric data, integrated with subbottom profiles and multichannel seismic data.

Canyons are seen to incise the continental slopes and (narrow) shelves offshore Calabria, in both northern and southern sectors. Canyons extend over lengths of tens of kilometers, with widths of up to 2 km, and shoulder-to-talweg relief in places greater than 200 m. Nine canyon systems are recognized, some consisting of isolated canyons, while others form hierarchic systems with five or more canyons merging to form dendritic morphologies (Fig. 3). In the southern sector, headwalls of large dendritic systems have a cauliflower morphology that can extend over perimeters more than 50 km long. Some canyons incise the shelf and may connect to onshore drainage networks, whereas others are restricted to the shelf edge or the slope.

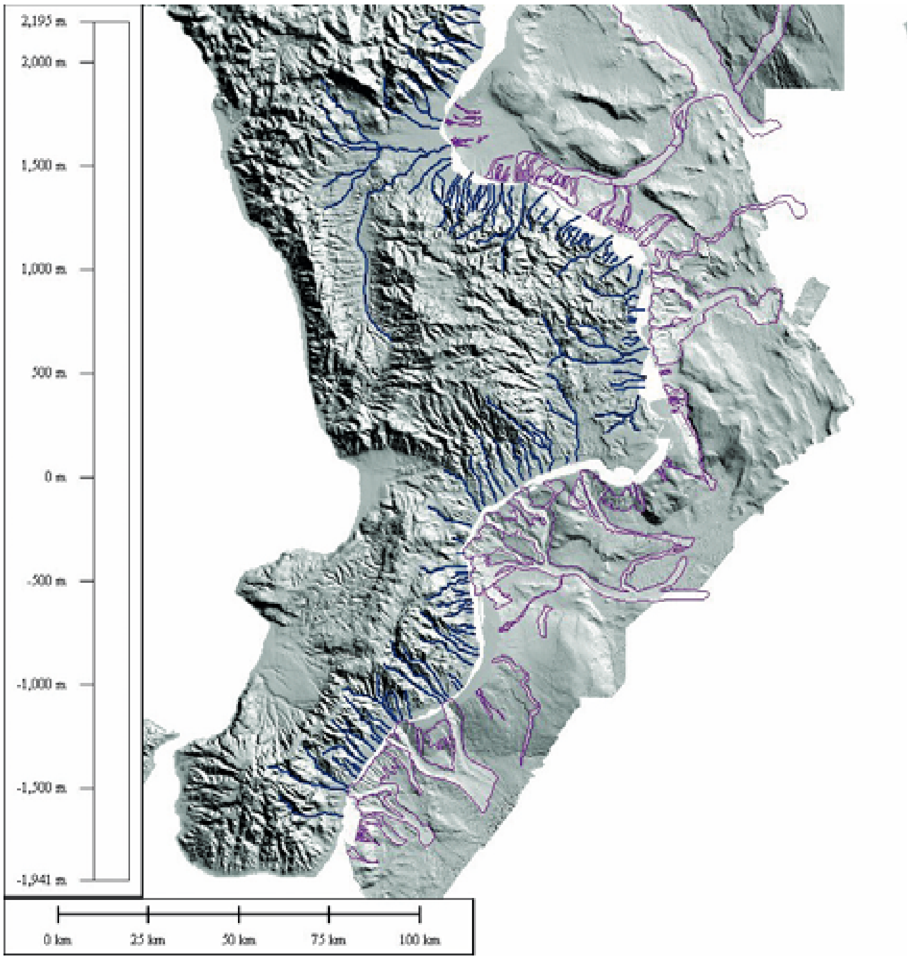


Figure 3. The nine submarine canyon systems incising the ICM (in white and purple). In blue the Calabrian hydrographic network.

In both the northern and southern sectors, seismic profiles across the Calabrian canyons show them to post-date a regional unconformity inferred to be of mid-Pleistocene age (Fig. 4). The age of the sediments is based on correlation to prominent unconformities observed within the onshore Crotone Basin (Fig. 4; Zecchin *et al.*, 2012, 2015). A mid-Pleistocene onset of canyon incision is consistent with the presence onshore of a fossil canyon of mid-Pleistocene age in the uplifted Crotone Basin (Zecchin *et al.*, 2011). This is quite an interesting result, as most Mediterranean canyons (especially from the Western basin) are inherited from erosion during the Messinian salinity crisis c. 5.5 Ma ago, whereas the Calabrian canyons have developed over much shorter timescales and independently of older erosional features (Fig. 4).

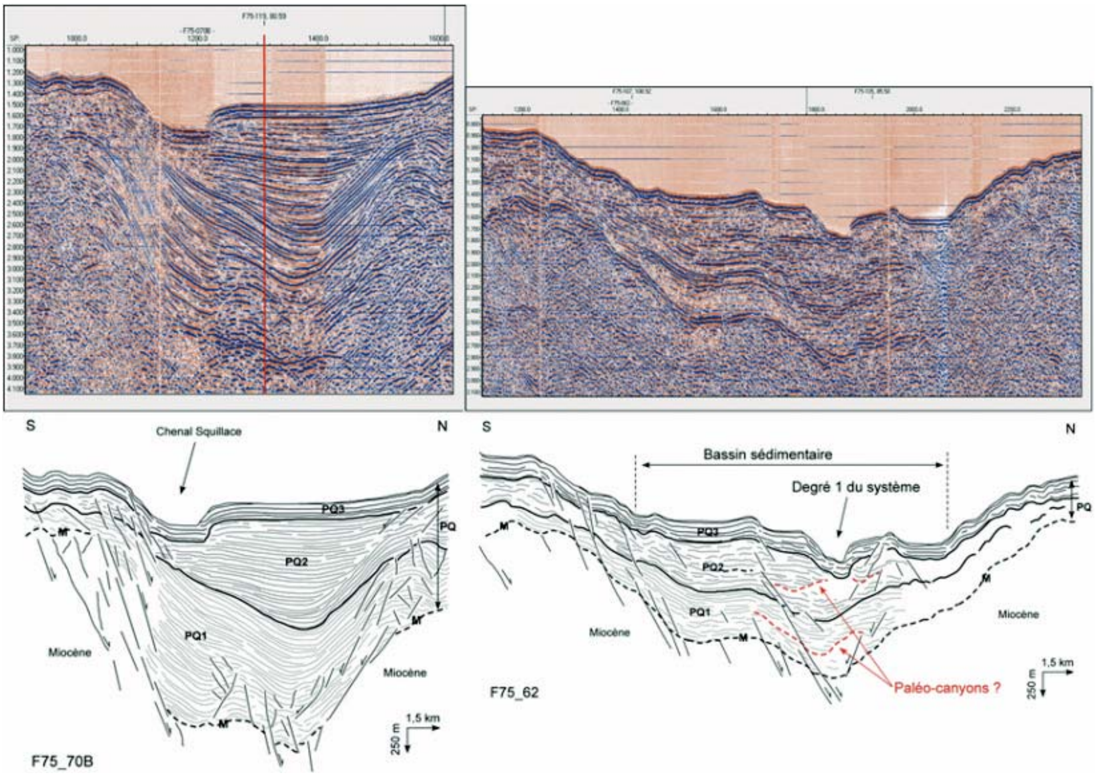


Figure 4. Seismic lines VIDEPI across the ICM margin and their interpretation. PQ1 lower Pliocene, PQ2 upper Pliocene-lower Pleistocene, PQ3 upper Pleistocene. Source: Coste (2014)

Despite their young age (<1 Ma), the canyons have been very dynamic, incising the margin over wide areas and to depths of more than 200 m. The supply of sediments from onshore erosion may have played a role in the development of some canyons, but the presence of canyons that do not reach the shelf indicates that retrogressive headward erosion has been an important part of their growth. We infer that most canyon systems, especially those in the southern sector where the continental slope is steeper, have been characterized by intense mass wasting processes in the form of slides and failures in the headwall areas and turbidity currents in the distal areas.

Many of the canyons of the ICM have the particularity of having their headwalls very close to the coastline (Fig. 2). Steep headwalls and observations of many small-scale slide scars support the inference of retrogressive (landward) erosion as an ongoing aspect of canyon dynamics. Some canyons thus represent a potential geohazard to coastal communities and local infrastructures (Fig. 5). An example is the Cirò Marina harbour that is built over the 5 km wide headwall of the Alice canyon system (Fig. 5C). Mass wasting related to the landward retrogression activity of the Alice canyon headwall have been considered responsible of frequent harbor damaging and for this reason regular and accurate monitoring should be planned in order to understand how fast and in which areas the headwall is approaching the coastline.

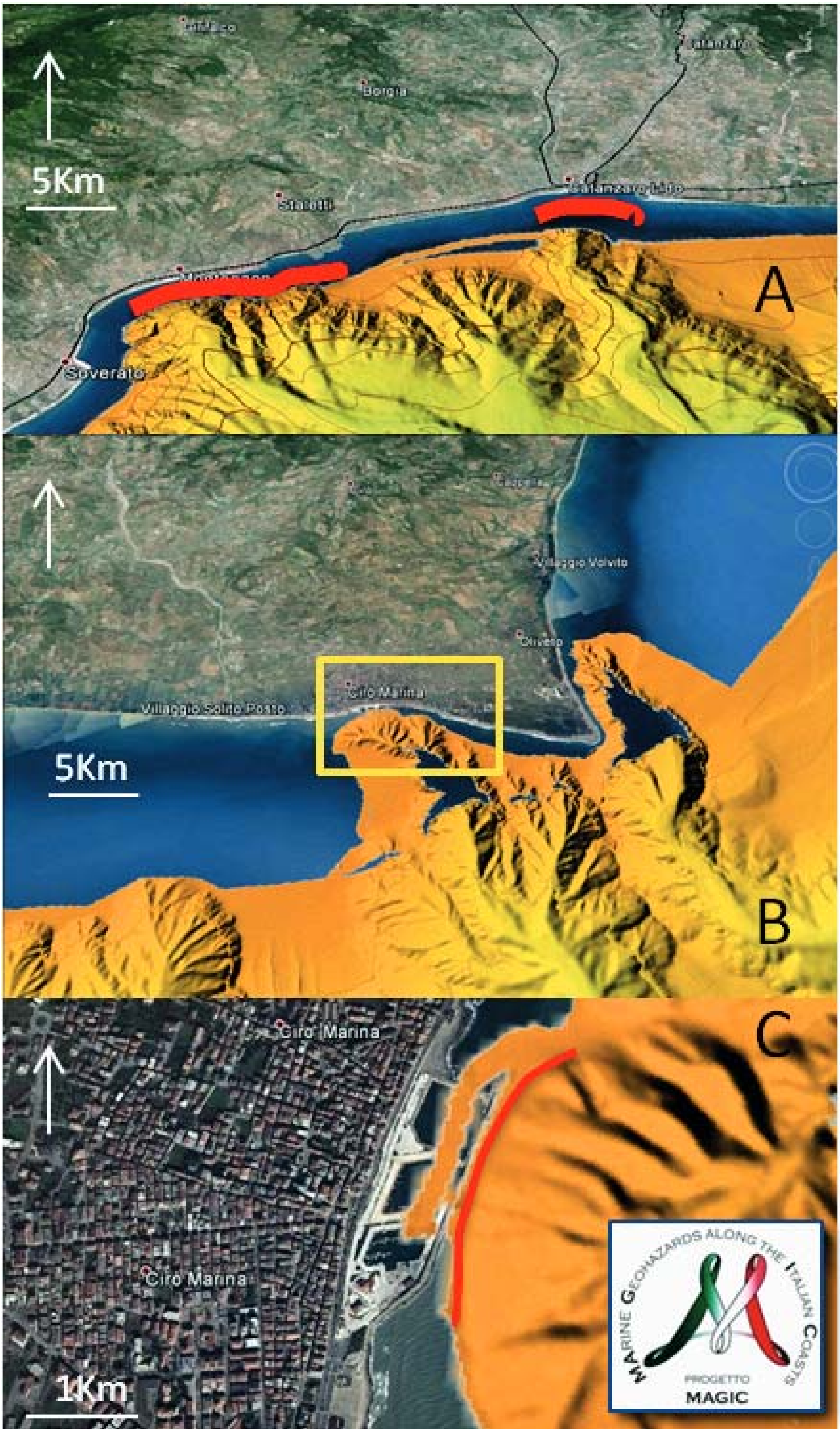


Figure 5. Examples of canyon headwalls incipient to the coastal areas and local infrastructures. A shows the Squillace canyon system (6 in Fig. 3). B shows the Alice canyon system (2 in Fig. 3). C is a zoom of the square box in B. Red lines indicate the inferred scarp of the canyon headwall.

Conclusions

Seabed and near-bottom geophysical datasets have been integrated to identify nine canyon systems along two sectors of the Ionian Calabrian margin. The tectonic setting has resulted in differing shelf-slope morphologies between the northern and southern sectors. It is not clear what is the origin of these features as they differ for shape and characters, but we infer both tectonic control (km scale vertical uplift the last 1Ma) and sea-level changes during the glacial-interglacial fluctuations as the two important long-term factors controlling the development of the ICM canyon systems through a combination of enhanced sediment supply and retrogressive erosion. Some canyon headwalls of the southern sector reach the coast; their continued retrogression represents a potential geohazard for coastal communities and infrastructures.

---

* this chapter is to be cited as:

Ceramicola S., Coste M., Praeg D., Migeon S., Zecchin M. 2015. Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea. pp. 157 - 163 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.

Submarine canyons and channels of the Tyrrhenian Sea: from geological observations to oceanographic, biological and hazards studies

Fabiano Gamberi

Istituto di Scienze Marine, ISMAR, Consiglio Nazionale delle Ricerche, CNR, Bologna, Italy

Introduction

The Tyrrhenian Sea sits in a complex geodynamic region dominated by the convergence between the African and Eurasian plates that results in the building of the Apenninic-Maghrebian chain and in back-arc basin opening. The two young basin plains of the Vavilov and Marsili back-arc regions, located at depths of more than 3000 m, are surrounded by intraslope basins developed on the eastern Sardinian, the northern Sicilian and the eastern Italian mainland margins (Fig. 1).

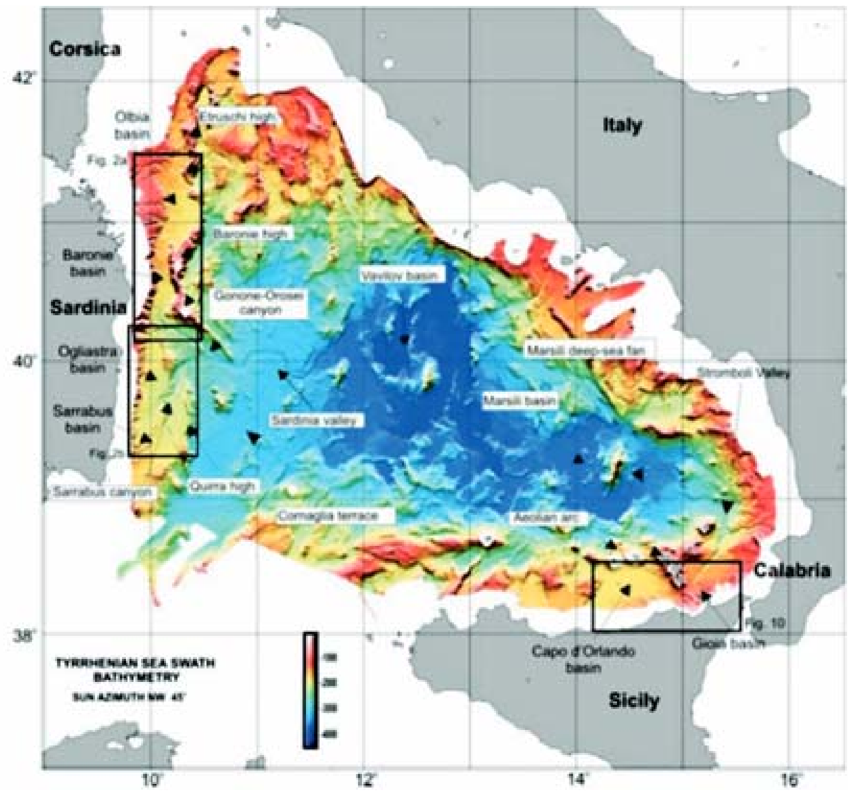


Figure 1. Bathymetric map of the Tyrrhenian Sea.

The Sardinian margin represents the passive margin of the Tyrrhenian Sea back-arc system and is characterized by negligible overall vertical movements, low seismicity, a relatively large shelf and a low-relief hinterland. The northern Sicilian and the western Calabrian margins are tectonically active, are characterized by high rates of vertical movements, have narrow continental shelves and an high-relief hinterland. As a consequence, the Tyrrhenian Sea represents a natural laboratory to test how different geodynamic settings impact the development and the architecture of submarine drainage networks from source to sink.

The Tyrrhenian Sea canyons show different characteristics of their head regions, some of them located very close to the present-day coastline and thus representing an element of hazards to infrastructures. The different positions of the canyons heads also imply that feeding systems to the deep sea are varied, being represented by direct hyperpycnal flow of riverborne sediment, by coastal sediment reworking due to oceanographic processes and by landslide often triggered by earthquakes. In addition, the different water depth of the heads of the canyons and their location with respect to shoreline physiography must impact on coastal oceanographic processes, creating local perturbations that can modify their regional characters. The canyon and channel systems of the Tyrrhenian Sea are both inactive and active – in the latter case showing a variety of erosional and depositional behaviours. In addition, they show the development of highly varied internal geomorphic elements that reveal a large environmental diversity that must be taken into account when studying biological responses to sedimentary and oceanographic processes and when working on deep-sea habitat mapping.

Canyon heads: the impact of oceanography, onshore geology, climate and sea level variations on sediment routing

In the northern part of the Sardinia margin, the continental shelf is up to 20 km wide. Canyons have heads that incise the shelf for a length of about 7 km. The shelf break is located at a depth of 150 m, whereas the canyon heads reach depth of only 100 m (Fig. 2).

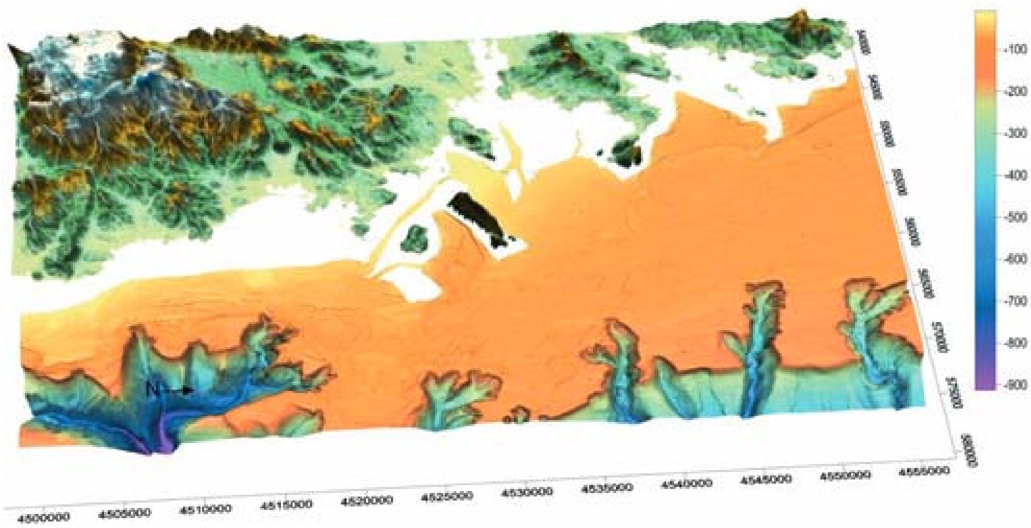


Figure 2. Shaded relief image of the northern portion of the eastern Sardinian margin.

The coastal systems developed during the last low stand of sea level are located at a depth of 120 m, thus during the last low stand of sea level rivers directly fed sediment to the heads of the canyons. Elongated depositional bodies, resulting from the reworking of coastal sediment due to long-shore currents are also present close to the canyon heads, showing that oceanographic processes contributed as well to the sediment budget delivered to the canyon heads during the last sea level low stand. The heads of the canyons are flanked landward by a continuous littoral barrier formed when the sea level was about 90 to 80 metres below present day. They bounded a lagoon seaward and therefore isolated the canyon heads from any input of riverborne sediment, thus dictating the onset of canyon deactivation during the first phase of the late sea level rise.

In the central sector of the Sardinian margin, the Orosei-Gonone canyon system represents an exception having its head very close to the shoreline (Fig. 3).

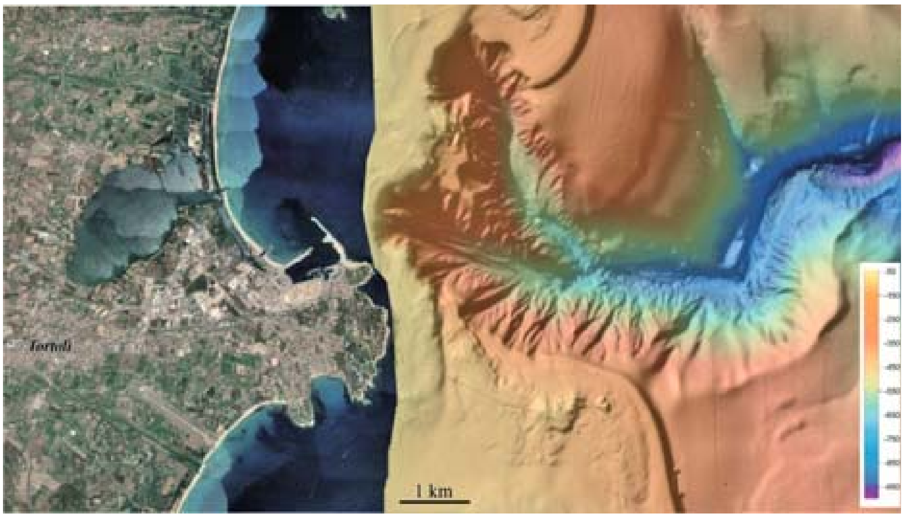


Figure 3. The Gonone canyon head located very close to the coast and to harbour infrastructures.

The Orosei-Gonone canyon system shows that the processes of canyon head retrogradation can be important and can be a source of hazards to coastal infrastructures even in passive margins. It also shows that the extent of canyon head retrogradation is not always directly related to its connection to large drainage area on land, since the Orosei-Gonone canyon head faces a very small river.

In the Sicilian margin many of the canyons have their heads very close to the coastline (Fig. 4).

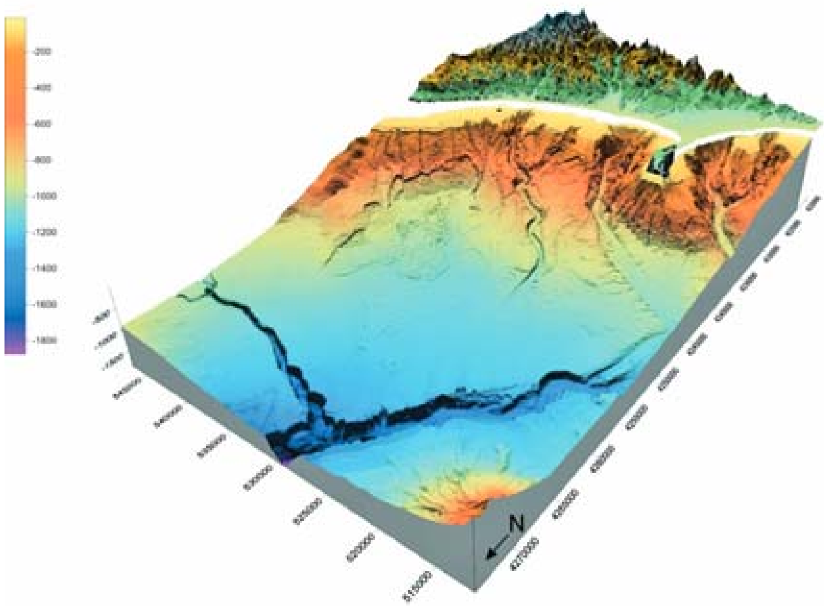


Figure 4. Shaded relief image of the northeastern Sicilian margin.

In this case it appears that at the present time the canyon heads are often directly fed by riverborne sediments particularly during the flash flood events that in recent years have been a typical catastrophic process in the area.

Figure 5. Shaded relief image of the head of the Milazzo canyon.

In many canyons of the Sicilian margin the canyon heads occupy a wide seafloor portion and can be an hazard to coastal infrastructure as shown in the image of Fig. 5 where channels that are located at the heads of the Milazzo canyons are adjacent to the piers of the Milazzo industrial area. In addition it appears that in some cases the canyon heads act as sink of sediment, causing sediment starvation along the shallow water areas and favouring coastal erosion and retreat.

Canyon course: different geomorphic elements represent a variety of environmental settings

The submarine channels and canyons of the Tyrrhenian Sea are characterized by both erosional and depositional attitude and features, sometimes varying along very short distance within the same system. Local closed depressions correspond to areas of focussing flow erosional behaviour in plunge pools, and form circular or elongated localized features. They can be up to 3 km long and up to 50 m deep and thus give rise to longitudinally isolated environments along a channel or canyon course.

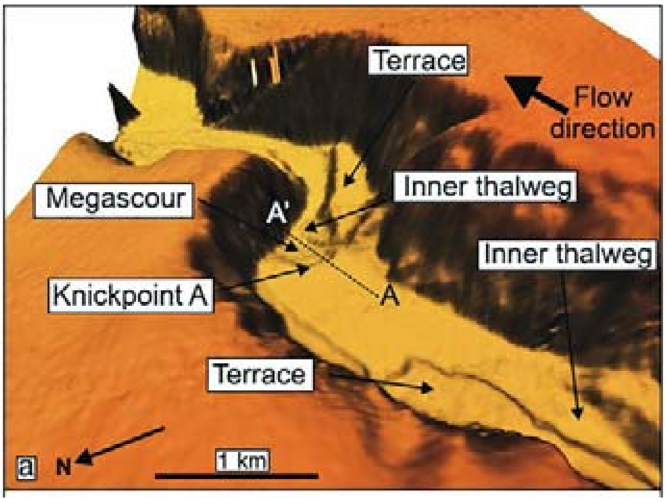


Figure 6. Shaded relief image of one sector of the Caprera channel in the Sardinian margin.

A further common erosional element that causes longitudinal environmental variations along channels and canyons consists of cross channel escarpments that coincide with gradient increase and are often associated with smaller scale erosional crescentic scours (Fig. 6). These erosional escarpments can have variable dimensions, going from small, 10 m high escarpments, to large, up to 100 m high features. In some cases they separate two sectors of a channel or a canyon with depositional attitude, thus representing areas of longitudinal environmental discontinuity.

Erosional channels show in general steep flanks and a V-shaped axial incision; however, deposition can occur locally also in this type of conduits. This is for example the case of channels in which incision is accompanied by a progressive narrowing that leaves terraces hanging at various heights above the entrenching channel floor (Fig. 6). Deposition of mainly fine grained and thin bedded turbidites occur in the terraces from the upper, low-energy part of flows funnelled within the channel; coarser and thicker bedded facies deposited by the higher energy lower part of flows are however found when the terraces are at a low height above the channel axis.

Depositional channels are also characterized by a variety of internal elements. Meandering channels show depositional elements that are developed mainly on the inside of bends that are often comparable to river point bars (Fig. 7).

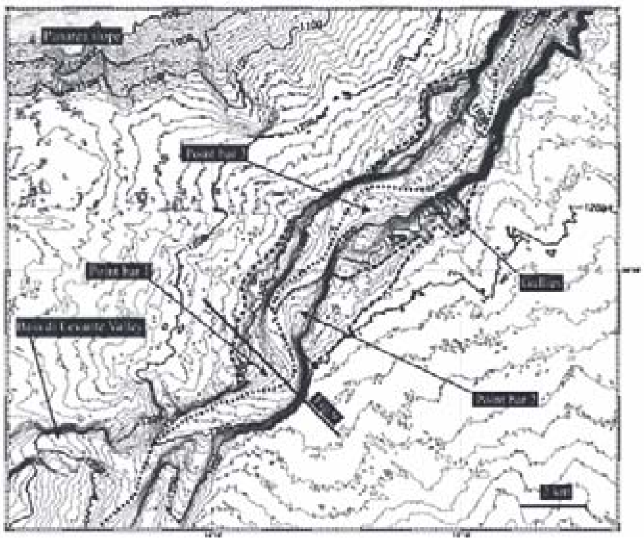


Figure 7. Bathymetric map of a sector of the Stromboli slope valley.

Meandering depositional channels are often characterized by a single channel element, but they also display sometimes the development of multi-channel tracts, likely as a result of flow pathway divergence connected with the dynamics of sinuosity development. Single thread mendering channels also show longitudinal variations with formations of knickpoints and depressions of variable sizes. This pattern appears to be dictated by the varying character of flows along a single meandering pathway creating variable environmental settings.

Multiple-channel tracts develop also within straight channels or canyons. They are often associated with mid-channel and side-attached bars. In some of which, seismic lines appear to substantiate that lateral accretion processes are the principal growth motif (Fig. 8).

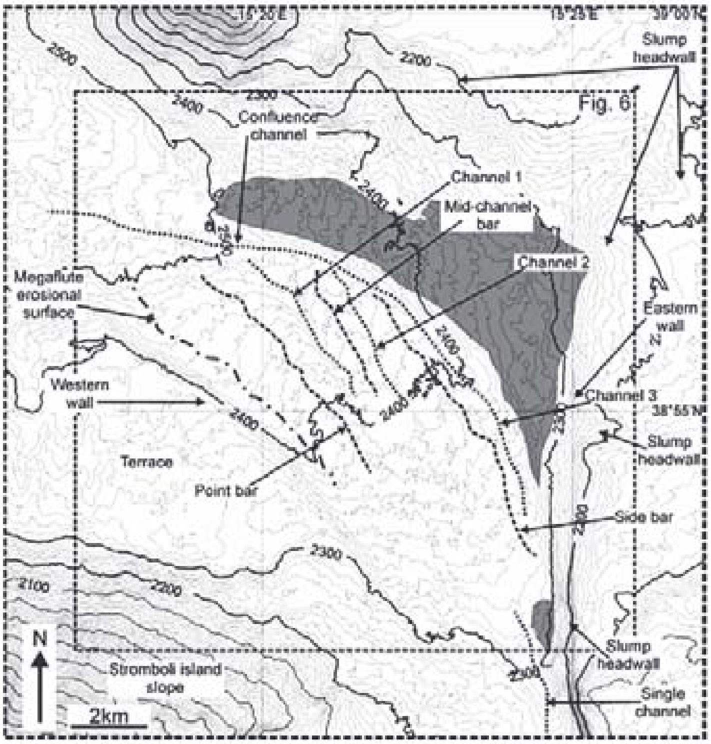


Figure 8. Bathymetric map of one distal sector of the Stromboli slope valley.

This setting appears to be best developed in relatively large and low gradient channels, often in coincidence with conduit enlargement.

Flat, relatively featureless canyon and channel floor are also characteristic of some systems. Also in this case a gradual transition between a channel-axis and a channel–margin depositional setting is sometimes evident. Channel margin environments have a seismic facies that is indicative of thinner and finer grained deposits deposited by lower energy flow portions than their correlative coarser-grained facies within the axial part of the conduit.

Smaller scale geomorphic elements, such as sediment waves and scours are developed in many tracts of canyons and channels. Sediment waves appear ubiquitous, developed on the heads of canyons and channels. Their wavelength can give indication of the grain-size of the corresponding deposits and of the variations of energy level at the seafloor. Scours have a variety of forms and dimensions and represent localized high-energy erosional environments within otherwise lower energy depositional settings.

---

* this chapter is to be cited as:

Gamberi F. 2015. Submarine canyons and channels of the Tyrrhenian Sea: from geological observations to oceanographic, biological and hazards studies. pp. 165 - 170 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.

The long-term evolution of submarine canyons: insights from the NW Mediterranean

D. Amblas[1], M. Canals[1] and T.P. Gerber[2]

[1] *GRC Geociències Marines, Universitat de Barcelona, Catalonia, Spain*
[2] *Statoil, Research Center Austin, Austin, Texas, USA*

Abstract

A fascinating aspect of submarine canyons is that they resemble river valleys. As with fluvial systems, the study of submarine canyon and channel long profiles sheds light on the fundamental processes controlling their long-term form and dynamics (i.e. morphodynamics). In this short paper we summarize a number of recent studies, based mainly on observations and measurements from the Catalano-Balearic Basin (NW Mediterranean), that relate the long-profile form of canyons and channels to the processes that control their evolution. We briefly present a model for the long-profile curvature of submarine canyons that includes the combined effects of turbidity currents and background (i.e. hemipelagic) sedimentation, and compare the range of model profile shapes with those observed on the present-day NW Mediterranean slope. We then summarize work on a 3D seismic volume over the present-day continental slope that documents how submarine canyons and their interfluves co-evolve on constructional (i.e. prograding) margins, work that has broadened our view of canyons as purely erosive features to one in which canyons can persist through long-term margin growth. Finally, we discuss evidence from the present-day seafloor and shallow subsurface for long-profile adjustment at or near tributary junctions in the extensive Valencia deepwater channel network.

Introduction

The intriguing similarity between submarine canyons and river valleys was first recognized in early bathymetric measurements along continental margins (Daly, 1936). The apparent geomorphic similarities between fluvial and deepwater systems – similarities that are now well documented in swath sonar maps of the seafloor – has motivated numerous comparative studies (Shepard, 1981; McGregor *et al.*, 1982; Pratson and Ryan, 1996; Mitchell 2005, 2006; Straub *et al.*, 2007; Amblas *et al.*, 2011). Central to all of these studies is the question of why such similar landforms should exist in subaerial and submarine environments when (1) few continental slopes have ever been exposed to subaerial processes and (2) the surface processes that shape landscapes and seascapes differ in some important ways. Clearly these differences are in many cases less important than the similarities in the formative processes. So what can we say about these similarities?

The total relief observed in many terrestrial mountain belts is comparable to that observed along the world's continental slopes. Consider the NW Mediterranean Basin (Fig. 1). The height difference between the highest eastern Pyrenean mountain range and the coastline is nearly 2900 m, similar to the maximum depths attained in the Catalano-Balearic Basin (Fig. 1). This observation reminds us that the orogenic uplift that generates subaerial relief has a submarine analogue, where marine shelf-to-basin relief is generated by a combination of tectonics (lithospheric extension or subduction at the transition to ocean crust) and sedimentation (the characteristic clinoform of continental margin stratigraphy). To the extent that this relief provides the potential energy for fluid flow and sediment transport, it is perhaps unsurprising that both environments are characterized by drainage patterns. Figure 2 shows a comparison between the headwaters of a river (Ter River) and a submarine canyon (La Fonera Canyon). These drainage systems share similar morphologies that include a main sinuous valley surrounded by tributaries with steep flanks cut by well-developed gullies. Interestingly, at 18 km downstream in both the subaerial and submarine valleys we observe the same height difference (1300 m) and comparable contributing drainage areas (140 km^2 in the river and 120 km^2 in the canyon).

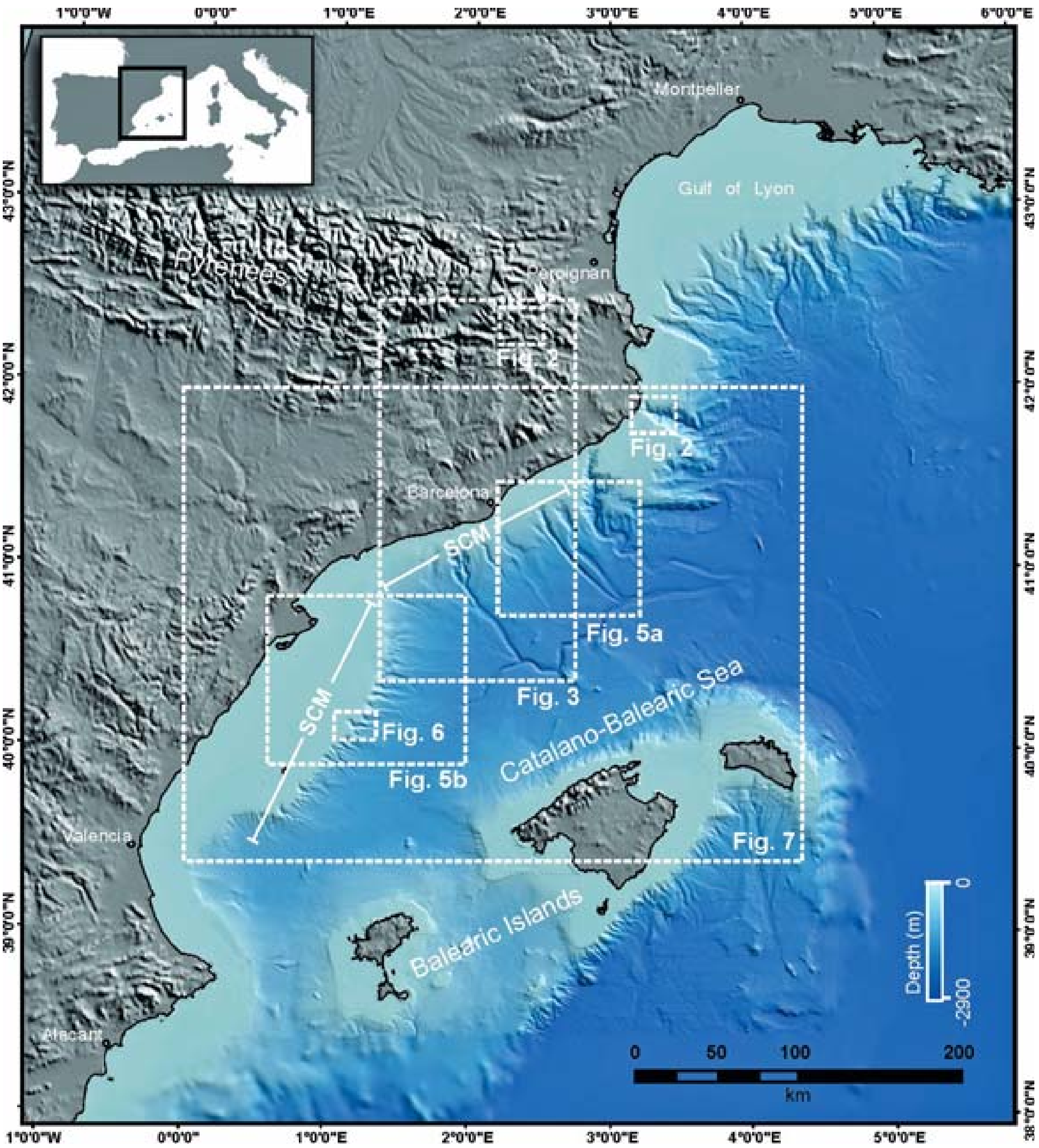


Figure 1. Shaded relief image of the NW Mediterranean Basin. The elevation data combines different multibeam bathymetry data sets from the University of Barcelona, the Spanish Institute of Oceanography, IFREMER, and global digital databases. White boxes show location of Figures 2, 3, 5, 6 and 7. SCM, South Catalan margin; EM, Ebro margin.

On land we associate these patterns with the action of rivers and debris flows (e.g. Pelletier, 2004). And we generally assume that submarine debris flows and turbidity currents generate the corresponding patterns on the seafloor (Shepard, 1981; Parker, 1982; Pratson and Coakley, 1996; Imran *et al.*, 1998; Harris and Macmillan-Lawler, this volume). As our interest is in the cumulative effect of surface processes acting over timescales of landscape evolution, we will briefly consider in what follows the geomorphic transport laws widely used to model terrestrial landscape evolution and those proposed for deepwater environments. In doing so we will focus on the long-profile (or along thalweg) shape of rivers and submarine canyons and channels, since they are easily measured and can be related directly to the predictions of process laws developed to explain them.

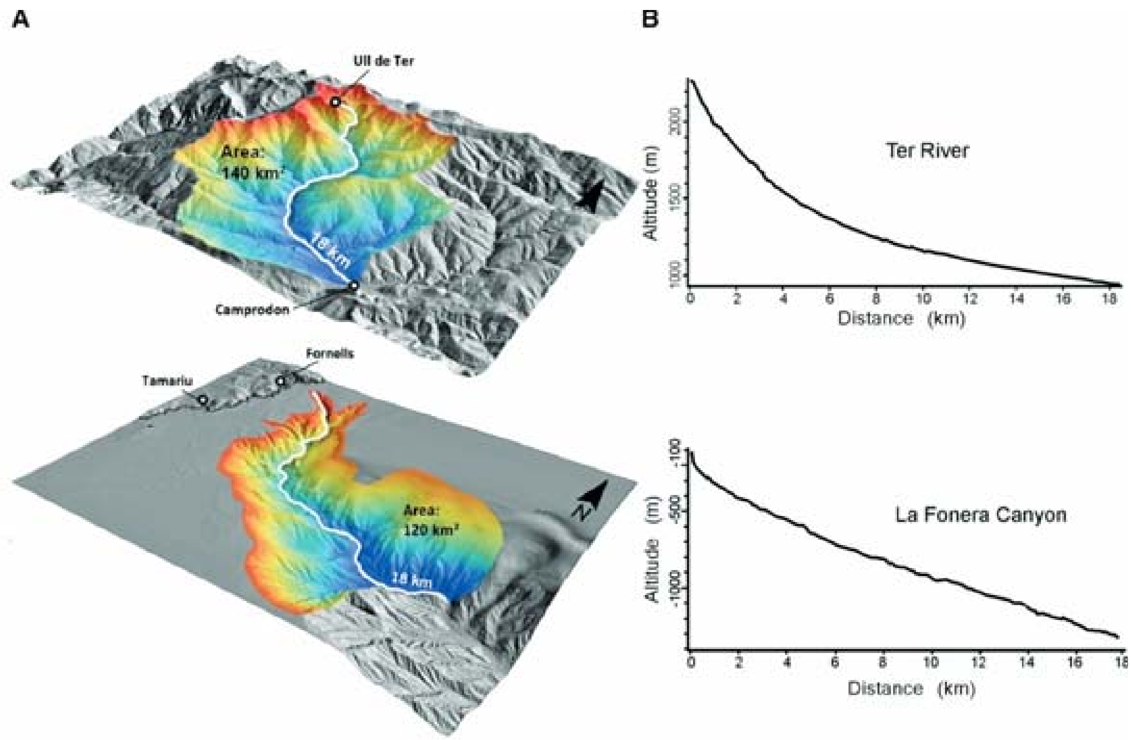


Figure 2. A) Morphometric comparison of the upper courses of Ter River and La Fonera Canyon. The resolution of the DTMs is the same in both cases (15 m). See location in Fig.1. B) Along-thalweg depth profile (i.e. canyon long-profile) of the upper course of Ter River and La Fonera submarine Canyon. Vertical exaggeration is x8 in both cases.

The long-profile shape of rivers and submarine canyons

Numerous measurements of submarine canyon and channel long profiles show smooth, concave-up shapes not unlike those observed along river thalwegs (Fig. 3). Explanations for the long-profile curvature of river profiles is well-established (Snow and Slingerland, 1987; Sinha and Parker, 1996; Sklar and Dietrich, 1998), and a number of studies – either by way of fluvial analogy or analysis of sediment gravity flow mechanics – have addressed the processes that are thought to contribute to long-profile concavity in submarine settings (e.g. Pirmez *et al.*, 2000; Kneller, 2003; Pirmez and Imran, 2003; Mitchell, 2005a; Gerber *et al.*, 2009). So what are these explanations, and how do they differ?

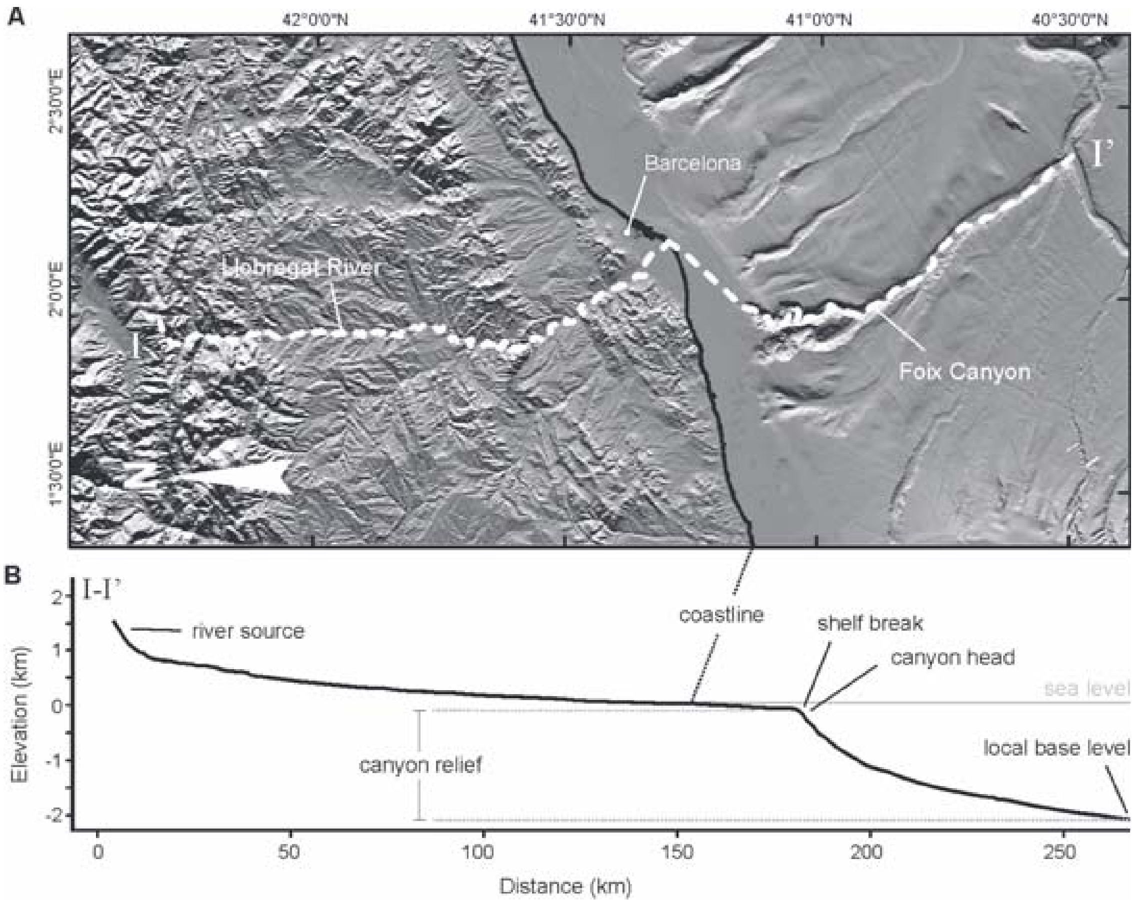


Figure 3. A) Shaded relief digital terrain model showing the thalweg trace of Llobregat River and Foix Canyon. B) Ensemble plot of Llobregat River and Foix Canyon long-profiles.

There are two primary controls on long-profile concavity in rivers: (1) increasing water discharge with downstream distance due to increasing drainage area, and (2) deposition in alluvial basins due to a divergence in bedload sediment transport. Clearly only the first of these operates in bedrock rivers, generally described using a process law of the form

$$\frac{\partial \eta}{\partial t} = U - kA^m S^n \tag{1}$$

where $\eta(x,t)$ is bed elevation, $U(x,t)$ is the tectonic uplift rate, $A(x,t)$ is the contributing drainage area, $S(x,t)$ is the bed slope, k is a (dimensional) coefficient, and x is downstream distance (Howard *et al.*,1994; Kirby and Whipple, 2001). At steady-state with constant uplift, the bed slope can be expressed as

$$S = \left(\frac{U}{k}\right)^{\frac{1}{n}} A^{-\frac{m}{n}} \tag{2}$$

where the ratio m/n (>0) sets the channel concavity for increasing drainage area (or discharge) and the coefficient U/k controls the overall slope magnitudes. Mitchell (2004, 2005) argued that a similar relationship might govern submarine canyon long-profiles. In this view, U represents the background rate of hemipelagic sediment fallout that slowly builds the continental slope, while A is the drainage area defined upslope from a point in the canyon thalweg. To make this analogy, Mitchell (2004, 2005) equated larger drainage areas to a greater frequency of sediment gravity flows initiating on the slope. Note that this definition of *A* did not include the effects of flows originating landward of canyon heads on the continental shelf.

The surface evolution of alluvial basins is generally modelled using a diffusion equation of the form

$$\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x} \upsilon \frac{\partial \eta}{\partial x} - \sigma \tag{3}$$

where $\sigma(x,t)$ (>0) is the subsidence rate and $\upsilon(x,t)$ is a fluvial diffusivity that is linearly proportional to the stream discharge per unit width of channel q_w [L^2T^{-1}]. A detailed derivation of (3) is beyond the scope of this contribution (see Paola, 2000 for a thorough discussion). Of interest here is the long-profile form predicted by the relation. At steady state (3) can be written as

$$\frac{\partial^2 \eta}{\partial x^2} = \frac{\sigma}{\upsilon} + \left(\frac{1}{\upsilon} \frac{\partial \upsilon}{\partial x} \right) S, \; S = -\frac{\partial \eta}{\partial x} \tag{4}$$

For constant υ, the concavity of the alluvial long-profile is given by the first term on the RHS of (4). This is the depositional or 'storage' concavity and simply represents the decrease in slope required to for deposition to balance the subsidence. For a steady fluvial profile that progrades with constant velocity *V*, a similar term appears (VS/υ) representing the additional 'storage' concavity required to sustain progradation. The second term will increase this concavity if q_w (and hence υ) increase downstream.

Gerber *et al.* (2009) proposed a model for submarine canyon long-profiles that has analogies to both the bedrock (1) and alluvial (4) cases. They view submarine canyons on constructional margins as prograding landforms that advance basinward with the continental slope. As in the Mitchell (2004, 2005) model, a source term representing background sedimentation is included, but is defined by the average morphology (commonly sigmoidal) of the open continental slope. Sediment transport within the canyon is driven by turbidity currents, and is described by a simplified version of the 3-equation model of Parker (1986). For a steady long-profile in the traveling wave (progradational, *V*>0) coordinate $\tilde{x} = x - Vt$ the general relation is:

$$\frac{d^2 \eta}{d\tilde{x}^2} = \frac{S}{K} \left(V + \frac{dK}{d\tilde{x}} \right) - \frac{R_b}{K} \tag{5}$$

Here $R_b(\tilde{x})$ is a background sedimentation rate and $K(\tilde{x})$ is an effective diffusivity. Note that both a storage term and a term related to downstream increases in *K* favour long-profile concavity, which is offset by background sedimentation. As in the alluvial case, the diffusivity *K* increases with increasing discharge q_w (though nonlinearly). However, the dependence is unrelated to tributary input and its effect on bedload transport; rather, it arises from their representation of a suspended sediment balance for a turbidity current and an assumed relation for fluid entrainment into the flow. For a prograding, canyonized margin, (5) can be used to predict a continuum of long-profile forms with intercanyon and canyon end-members (Fig. 4). It can also be used to predict a graded (or 'bypass') long profile (*V*=0). Development of the model was largely inspired by – and subsequently used to explain – observations showing smooth long-profile concavity along canyons in rather different slope settings along the passive NW Mediterranean margin.

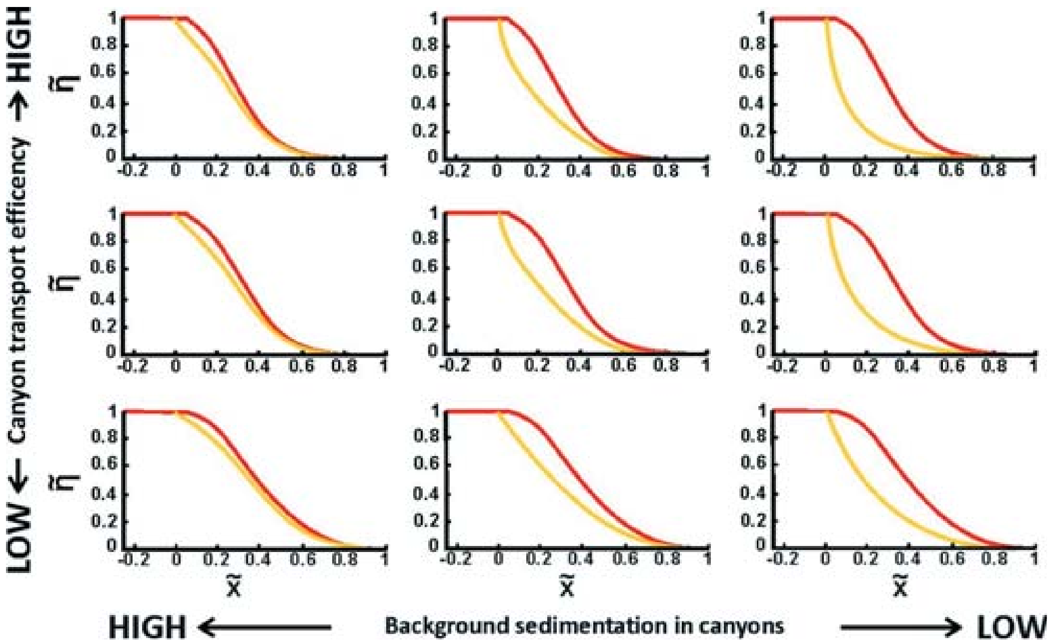


Figure 4. Matrix of canyon (yellow) and intercanyon (red) profiles for a range of canyon transport efficiency, which limits concavity, and fractions of background sediment storage, which limits convexity. Profiles are computed with analytical solution to the morphodynamic model for the long-profile shape of submarine canyons (Gerber *et al.*, 2009).
Adapted from Gerber *et al.* (2009).

On the South Catalan margin, a few large canyons are incised into a rather narrow shelf and extend across a smooth low-gradient slope (Amblas *et al.*, 2006). Arenys and Besòs canyons show a single entrenched chute with a nearly constant width and morphology from the shelf break to the canyon mouth (Fig. 5a). These canyons display a nearly constant width and morphology from the shelf break to the canyon mouth, and a single entrenched chute in seismic cross section (Gerber *et al.*, 2009). These observations suggest significant long-term sediment bypass to the contiguous Valencia Channel. The concave-up curvature displayed by the long-profiles of these canyons indicates that turbidity-current throughput exceeds background inputs to the canyons (Gerber *et al.*, 2009).

In contrast, the Ebro margin canyons are numerous and generally display low relief, most heading at or near the edge of the wide Ebro continental shelf (Fig. 5b). The long-profile of these canyons generally displays a concave-up curvature, similar to those observed along the South Catalan margin (Amblas *et al.*, 2011). However, a recent subsurface study based on a 3D seismic cube in the vicinity of Orpesa Canyon shows a convex-concave (sigmoidal) long-profile curvature on its mid-Pleistocene ancestor (Amblas *et al.*, 2012; see next section). This change in long-profile curvature has been interpreted as a shift to a canyon dominated by turbidity currents from one strongly influenced by the pattern of sedimentation that built the open-slope canyon interfluves (Amblas *et al.*, 2012). The progressive steepening of the Ebro margin from mid-Pleistocene to present (Kertznus and Kneller, 2009; Amblas *et al.*, 2012), and the effect of canyon capture and piracy (Lai *et al.*, 2013) would have determined the observed change in sedimentation style. It is relevant to note that in tectonically active margins, like the Sicilian margin, the convex-up curvature of the long-profile of submarine canyons has been interpreted as a consequence of tectonic uplift (Lo Iacono *et al.*, this volume).

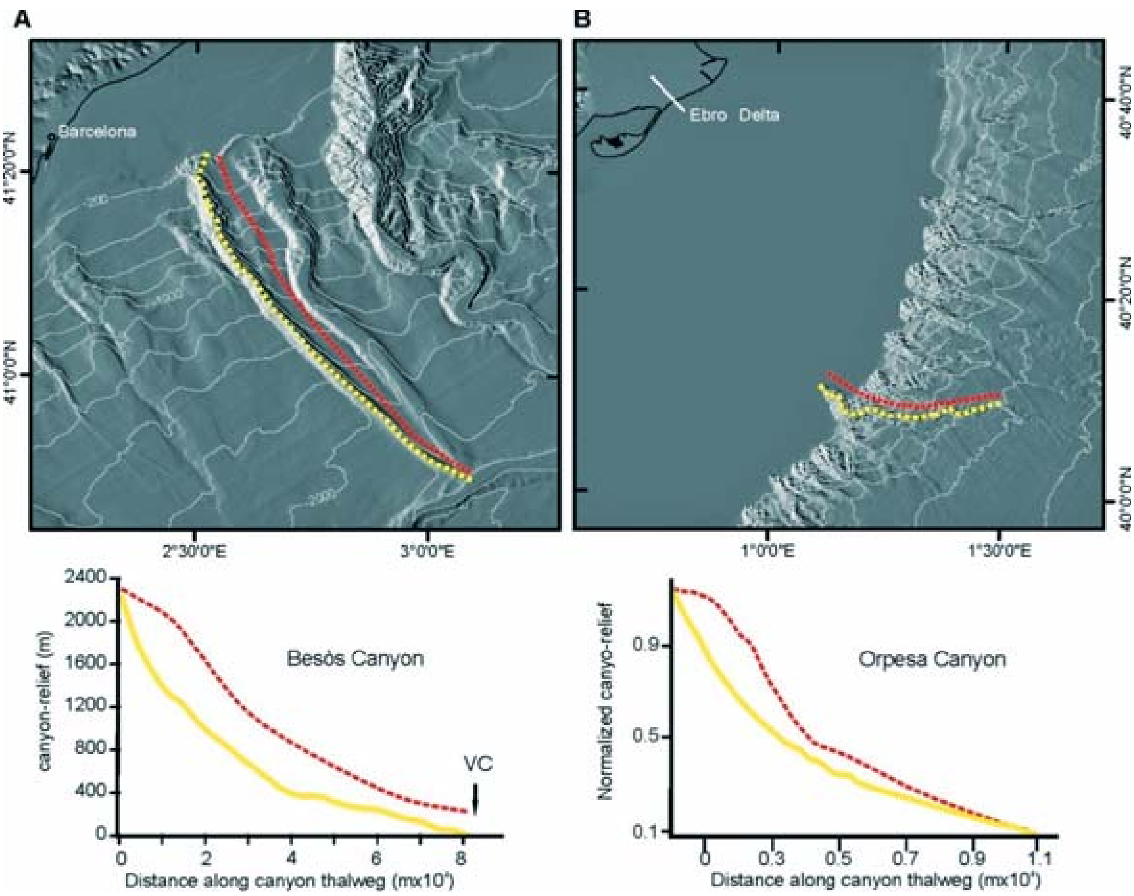


Figure 5. (a) Shaded relief image of the Southern Catalan margin and the Ebro margin. See Fig.1 for location. (b) Long-profiles of Besòs and Orpesa canyons (yellow) and their nearby interfluves (red). 'VC' denotes junction with Valencia Channel.

Submarine canyons in net depositional margins

Increasingly available 3D seismic data sets show that many modern submarine canyons have coevolved together with their interfluves during outbuilding of the continental margin (e.g., Wonham *et al.*, 2000; Deptuck *et al.*, 2007; Straub and Mohrig, 2009; Amblas *et al.*, 2012). The predominant view of canyons as purely erosive features (Shepard, 1981) implies that buried canyons represent submarine landforms that are rapidly cut and then passively filled. The Danube Canyon in the Black Sea (Popescu *et al.*, this volume) and the Rosetta Canyon in the Egyptian continental margin (Mascle *et al.*, this volume) show good examples in this regard. An alternative view is that some long-lived canyons can persist (i.e., maintain their overall morphology) over timescale during which significant margin progradation occurs. For this to occur there must be net sediment storage, both within the canyon and along the open slope. The model summarized above (Eqn. 5) has been used to represent this case (Fig. 4), and in essence treats canyons on constructional margins as clinoforms which, together with intercanyon slopes, define the strike-averaged long profile shape of the margin.

The aforementioned 3D seismic cube, provided by BG Group through the Spanish project EDINSED3D (CTM2007-64880/MAR), shows prograding and aggrading shelf-margin clinoforms with the canyon incising the outer shelf and slope near Orpesa Canyon, on the Ebro margin (Amblas *et al.*, 2012). A seismic profile coupling the modern Orpesa thalweg with its underlying mid-Pleistocene surface reveals a general subparallel stacking pattern of moderate- to high-amplitude seismic reflections, similar to the prograding clinoform architecture observed in the same chronostratigraphic interval outside the canyon (Fig. 6). This seismic architecture indicates long-term net sediment storage in the canyon, despite the likely occurrence of periods of erosion and transient disequilibrium that could be associated with sea-level lowstands. This pattern of nested canyon strata beneath the Ebro shelf and slope has been observed elsewhere on the margin (Field and Gardner, 1990; Bertoni and Cartwright, 2005).

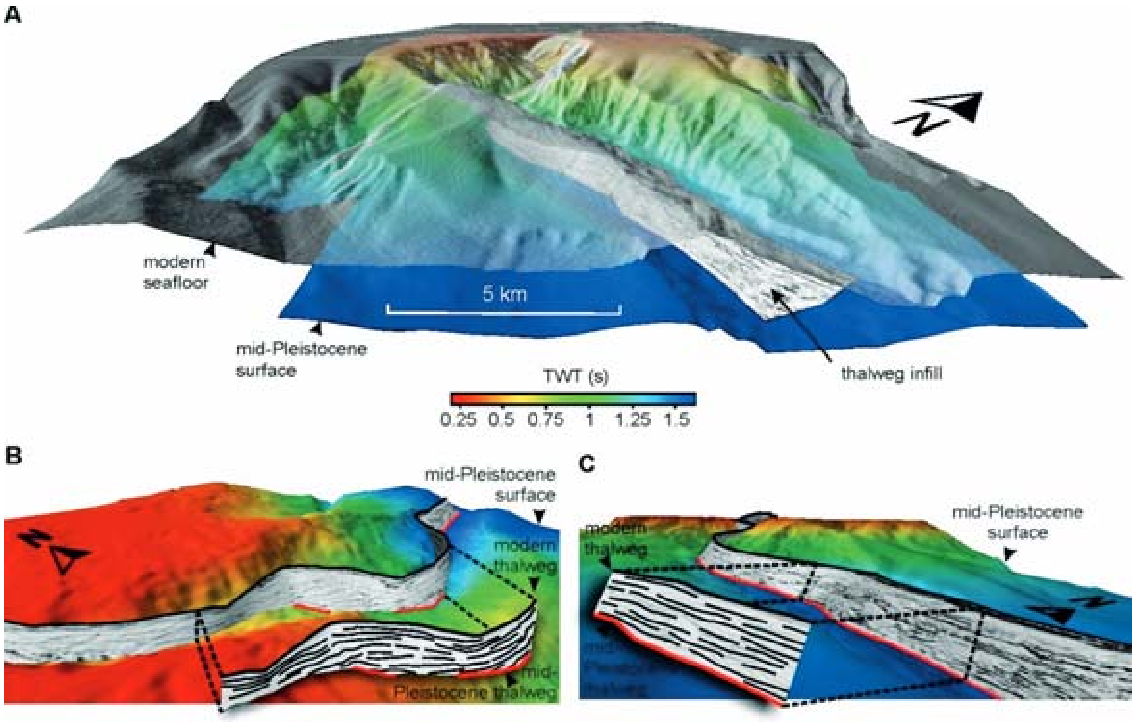


Figure 6. A) 3-D view of stacked modern and mid-Pleistocene surfaces around Orpesa Canyon (see Fig. 1 for location) along with the seismic profile showing the thalweg infill. TWT, two-way traveltime. B and C) 3-D view of mid-Pleistocene surface around Orpesa canyon with the seismic profile coupling the modern and the mid-Pleistocene thalweg.

Equilibrium and transience of submarine canyons

Submarine canyons and channels show discontinuities in their long profile which resemble widely observed subaerial knickpoints. In river basins, knickpoints are generally interpreted as evidence for downstream base level fall, and their form has been used to infer erosion laws governing upstream migration (Howard *et al.*, 1994; Whipple and Tucker, 2002). Submarine knickpoints have been shown to initiate where tectonic motion displaces the seafloor (e.g. Mitchell, 2006), where channel levees are breached (e.g. Pirmez *et al.*, 2000; Gamberi, this volume) or following submarine base level changes (e.g. Adeogba *et al.*, 2005). It is worth mentioning that, though not addressed here, the modeling framework summarized above can be used to investigate transient long-profile evolution.

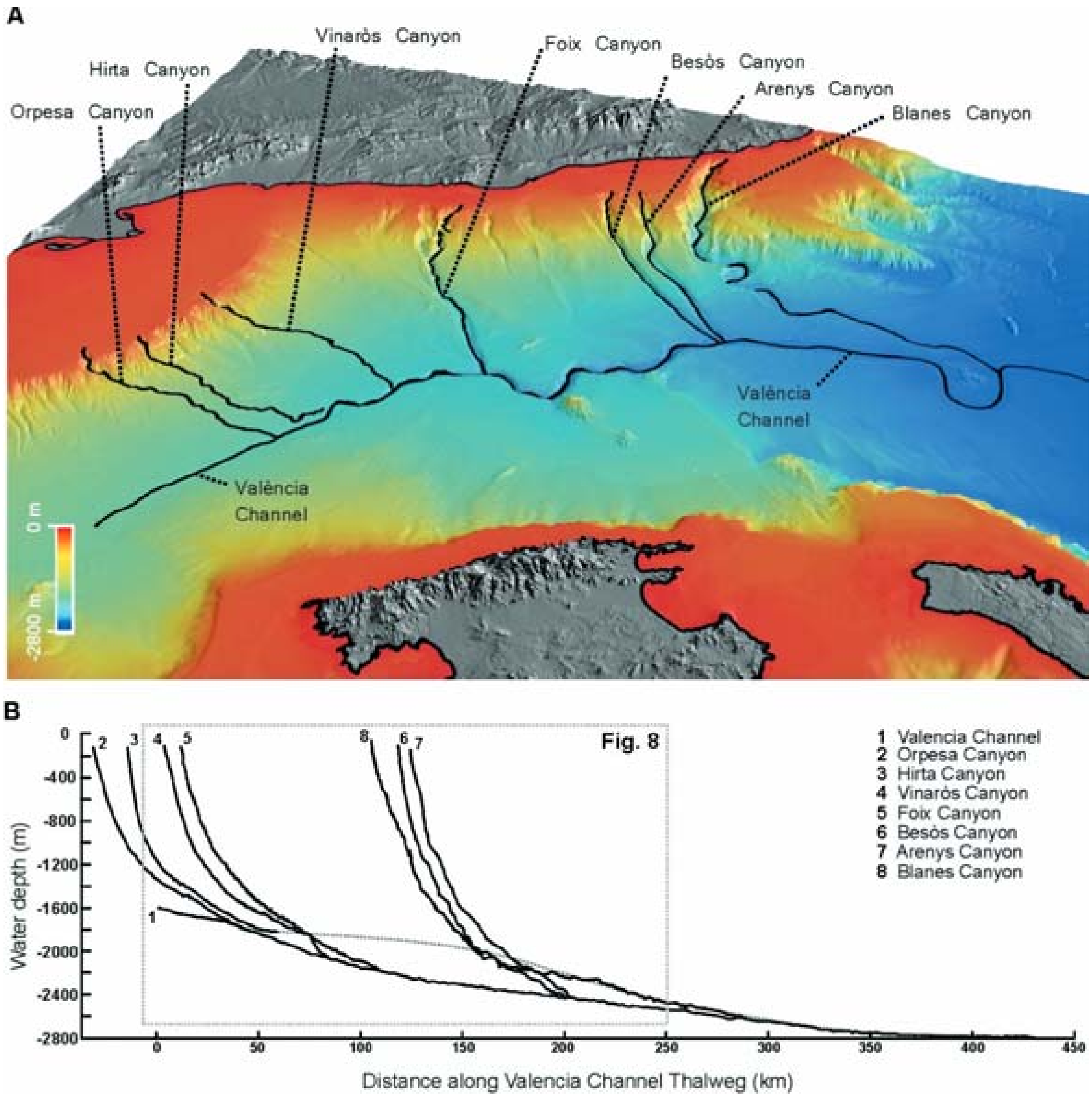


Figure 7. A) 3-D view of the Valencia Trough area showing the Valencia Trough turbidite system (black lines). See location in Fig.1. B) Longitudinal profiles of the main submarine valleys feeding the Valencia Channel from the southernmost modern tributary (Orpesa) to the Valencia Fan (distal end of plot) extracted from swath bathymetry (50 m grid resolution). Gray dotted curve is the smoothed bathymetric profile of the Valencia Channel margin parallel to its thalweg. Gray dotted box shows location of Fig. 8. Adapted from Amblas *et al.* (2011).

Discontinuities in canyon and channel long-profiles can provide clues about previous equilibrium conditions in single canyons or in submarine valley networks. One of the largest submarine valley networks in the Mediterranean is the Valencia Trough turbidite system (VTTS). The VTTS is located in the Catalano-Balearic Basin and routes sediment from a network of more than 1100 linear kilometres of submarine canyons and canyon-channel systems that share a common final conduit in the Valencia Channel (Fig. 7). The integrated analysis of channel thalweg bathymetry in the VTTS shows contiguous long-profiles through most of the submarine drainage network, although evidence for transient incision in the form of knickpoints is observed in two of its tributaries: Vinaròs and Hirta canyons (Fig. 8). By reconstructing the adjusted long profiles downstream of the knickpoints, it is possible to estimate the magnitude of channel adjustment in the drainage network. Based on the location and form of the unadjusted profiles upstream of the knickpoints, Amblas *et al.* (2011) suggested two possible triggering mechanisms for knickpoint initiation: (a) a change in sediment routing forced by a large debris flow at 11,500 yr BP (i.e. BIG'95 debris flow) that disrupted the upper reaches of the VTTS (Lastras *et al.*, 2002), and (b) a change in downcutting rates along the Valencia Channel middle course due to shifting sediment input during glacio-eustatic lowstands. Based on the timing of these, long-term average incision rates in the Valencia Channel have been estimated to be between 7.7 to 12.1 m kyr^{-1} near the Vinaròs junction and 3.3 to 5.2 m kyr^{-1} near the Hirta junction. These values should be taken as rough estimates for maximum entrenchment rates in the submarine channel.

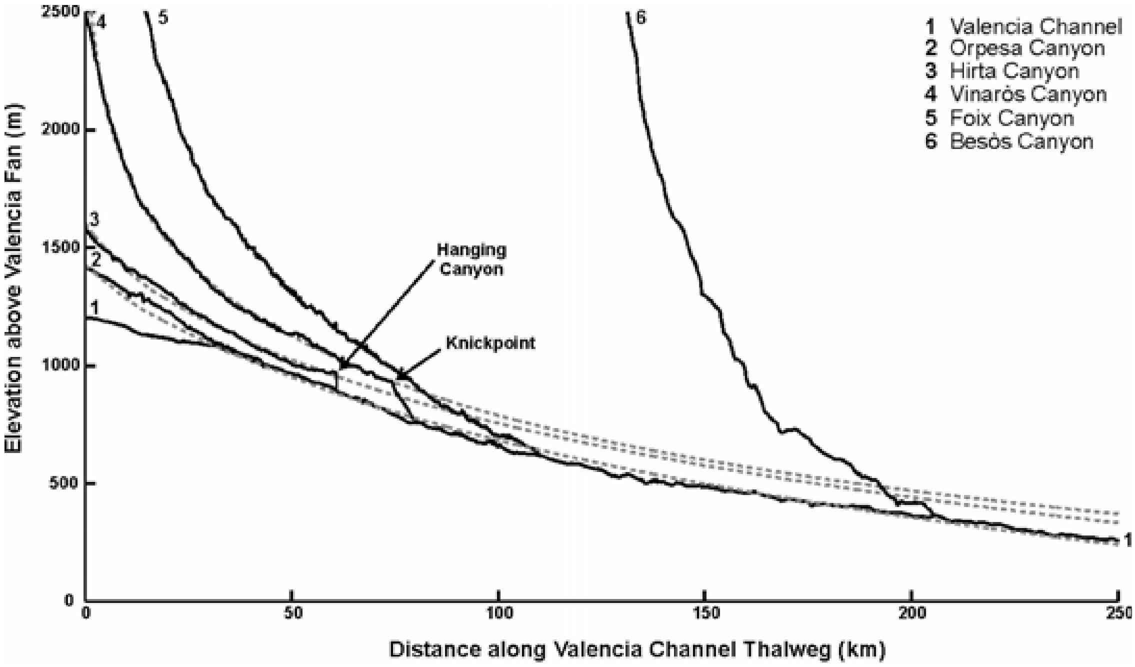


Figure 8. Zoom of the upper and middle course of the Valencia drainage network (see Fig. 6 for location) showing interpreted features of canyon-channel long-profiles. For Hirta and Vinaròs canyons, dashed lines show power-law fits to profiles above knickpoints that are projected below the knickpoints and down the Valencia axis. Also shown is a power-law fit to the Orpesa and Valencia combined long-profile. Modified from Amblas *et al.* (2011).

CONCLUSIONS

Advances in geophysical mapping of the seafloor and subsurface have provided new opportunities to understand Earth-surface processes along continental margin seascapes. We have adopted the approach of terrestrial geomorphologists in using the long-profiles of canyon and channel thalwegs to identify the signature of processes that sculpt the seafloor and build margin strata. Our natural laboratory has been the Catalano-Balearic Basin in the NW Mediterranean, where after decades of imaging we have documented in detail an extensive submarine drainage network that routes sediment from margins with contrasting morphologies through a single "trunk" conduit to an ultimate sink on the Valencia Deep Sea Fan. Observations from this margin have led to detailed field-based comparisons (Amblas *et al.*, 2006, 2011, 2012) and motivated and informed the development of morphodynamic models of submarine canyon long-profiles (Gerber *et al.*, 2009).

Acknowledgments

The authors acknowledge funding received from the Spanish RTD grants DOS MARES (CTM2010-21810-C03-01), VALORPLAT (CTM2011-14623-E) and NUREIEV (CTM2013-44598-R), and from EC contracts PERSEUS (GA287600) and MIDAS (GA 603418). GRC Geociències Marines is also recognized by Generalitat de Catalunya as an excellence research group (ref. 2014 SGR 1068). We especially thank G. Lastras, A.M. Calafat, R. Urgeles, B. De Mol, D. García-Castellanos, L.F. Pratson and S. Lai for valuable discussions during the progress of this study.

* this chapter is to be cited as:

Amblas D., Canals M., Gerber T.P. 2015. The long-term evolution of submarine canyons: insights from the NW Mediterranean. pp. 171 - 181 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.

Submarine canyons and related features in the Alboran Sea: continental margins and major isolated reliefs

Juan T. Vázquez[1], Gemma Ercilla[2], Belén Alonso[2], Carmen Juan[2,3], José L. Rueda[1], Desirée Palomino[1], Luis M. Fernández-Salas[4], Patricia Bárcenas[5], David Casas[6], Víctor Díaz-del-Río[1], Ferrán Estrada[2], Marcel.li Farran[2], Marga García[3,7], Emilio González[1], Nieves López-González[1], Bouchta El Moumni[8] Contouriber, Montera and Mower Teams

[1] *Instituto Español de Oceanografía, C.O. de Málaga, Fuengirola, Spain*
[2] *Instituto de Ciencias del Mar, CSIC, Barcelona, Spain*
[3] *Renard Centre of Marine Geology, Dept. of Geology and Soil Science, Gent University, Belgium*
[4] *Instituto Español de Oceanografía, C.O. de Cádiz, Spain*
[5] *Departamento de Análisis Matemático, Facultad de Ciencias, Universidad de Málaga, Spain*
[6] *Instituto Geológico Minero de España, Madrid, Spain*
[7] *Instituto Andaluz de Ciencias de la Tierra, CSIC, Granda, Spain*
[8] *Université Abdelmalek ESSAADI, Larache, Morocco*

Abstract

The analysis of a data set of multibeam bathymetry plus high resolution seismic and parametric profiles allow us to characterize the geomorphologic units on the Alboran Sea-floor as well as the evolution of morpho-sedimentary systems along the Pliocene and Quaternary, later than the main erosive Messinian event. Since the opening of the Gibraltar Straits, the sedimentary evolution of this basin has been controlled by the interchange of water masses between the Atlantic Ocean and the Mediterranean Sea. Basin physiography is also a consequence of the Pliocene-Quaternary compression which has progressively uplifted the sourrounding reliefs and deforms the interior and the margins of the basin. On this scenario, several submarine canyons and gullies have been developed in this basin which traverse especially the northern margin and the flanks of the Northern Alboran Ridge, without affecting the African margins. This fact must be related to the action of bottom contour currents which constitute the main morpho-sedimentary process. The influence of water masses distributed the sedimentary input carried by rivers and coming from the erosion of surrounding ranges. In the southern margin of this basin this influence is stronger and inhibits the development of transversal submarine canyons.

Introduction

The Alboran Sea constitutes the westernmost physiographic unit of the Mediterranean Sea. It is a semi-enclosed basin bordered by the Iberian and African margins and it is divided in two main basins (Eastern Alboran and Western Alboran) connected by a narrow corridor (Alboran Through) and two main intra-slope basins (Southern Alboran and Motril). Its physiography is characterised by narrow continental shelves, pseudo-concentric continental slopes, two wide marginal plateaus (MP): the Moulouya MP on the south-eastern continental slope and the Djibouti-Motril MP on the northern one, and several morphologic traits (structural and volcanic highs and ridges) (Fig. 1).

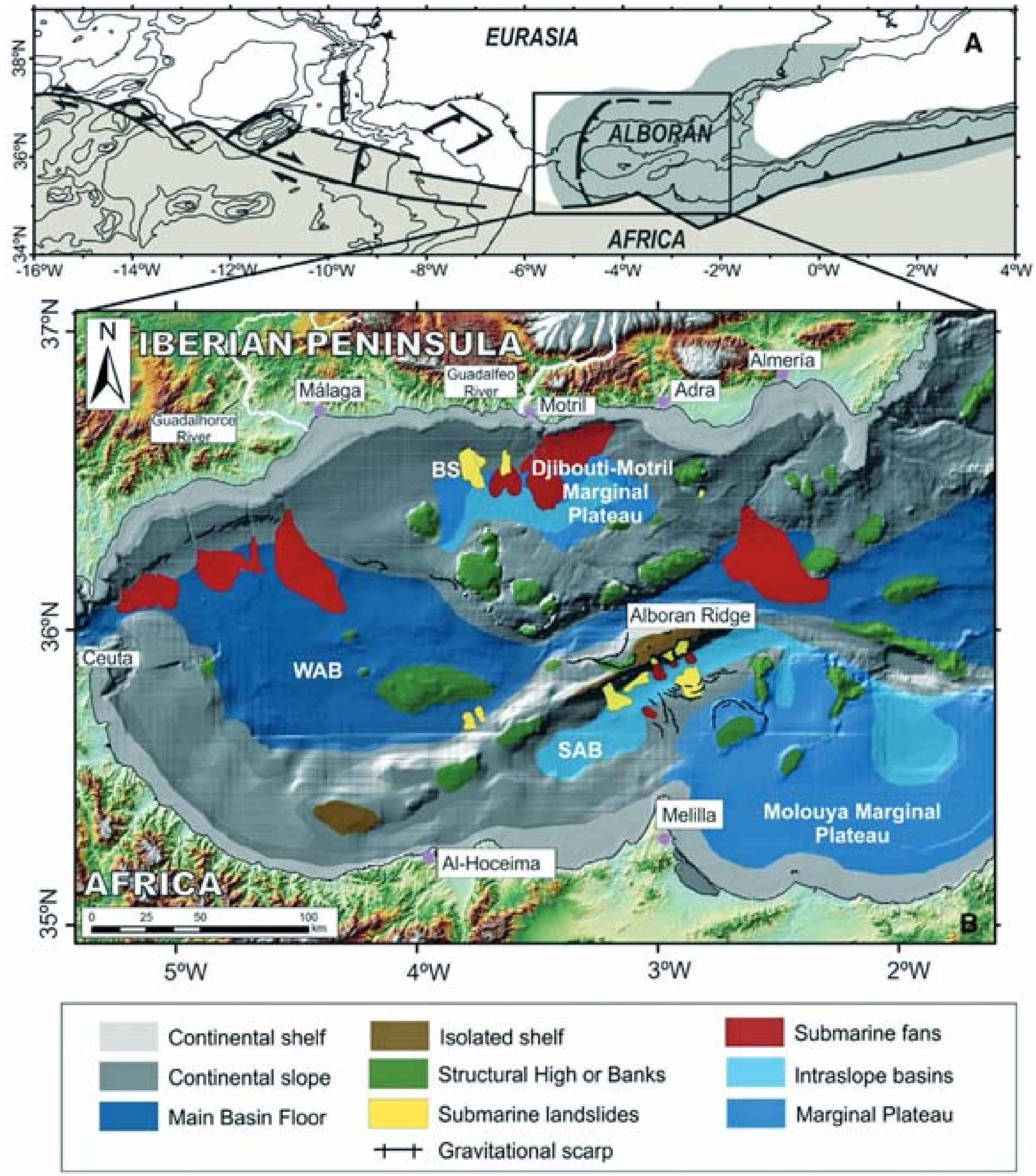


Figure 1. (A) Plate-tectonic scheme of the Ibero–Maghrebian region (modified from Vázquez and Vegas, 2000). WAS: Western Alboran Subduction Zone. (B) Physiographic Map of the Alboran Sea basin plotted on a hillshade model. A compilation of multibeam bathymetry (50 × 50 m) has been used for the construction of this model and has been plotted on a general hillshade model based on ETOPO bathymetry (1000 × 1000m). On land, a DTMmodel has been used based on the 1° × 1° files available from the 2000 Shuttle Radar Topography Mission, the resolution is about 90 m. BS: Baraza slide. SAB: South Alboran Basin, WAB: West Alboran basin. (Modified from Macías *et al.,* 2015).

Atlantic and Mediterranean water masses are connected through the Strait of Gibraltar and they meet and interact in the Alboran Sea. This oceanographic gateway controls the water masses changes and the complex physiography of the Alboran Sea Basin conditions the dynamics of these masses. In this regard the distribution of ridges, seamounts and marginal plateaus acts as obstacles to the intermediate and deep flows. The present-day circulation is defined by three major water masses: 1) the surficial Atlantic Water (AW) characterized by <36–36.5 psu salinity, average temperature of 16ºC, extended down to 150-250 m water depth that describes two anticyclonic gyres, Western and Eastern; 2) low density (LD) Mediterranean water, formed by the Western Intermediate Water (WIW, 37–37.7 psu salinity, temperature of 12.9–13ºC, extended down 300 m water depth) and Levantine Intermediate Water (LIW, salinity of 38.5 psu, temperature of 13.1–13.2ºC), which on the Spanish continental slope only extends down to 600m water depth; and 3) the underlying high density (HD) Mediterranean water, formed by the Western Mediterranean Deep Water (WMDW, 38.40–38.52 psu salinity, temperatures of <12.7–12ºC) which is largely restricted to the Moroccan margin (below 180m water depth, deep basins and the Spanish base-of-slope below 600m water depth) (Millot, 2009 and references therein) (Fig. 2).

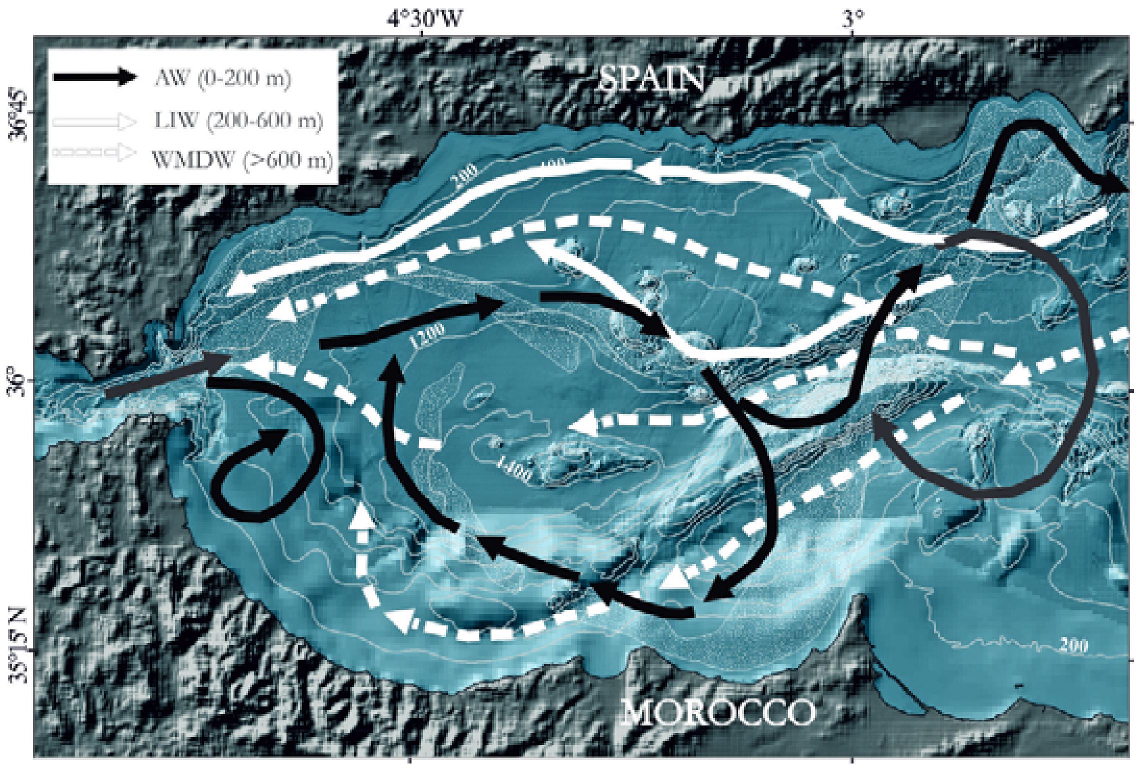


Figure 2. Bathymetric map of the Alboran Sea with the present-day regional circulation model. Legend: AW, Atlantic Water; WIW, Western Intermediate Water; LIW, Levantine Intermediate Water; WMDW, Western Mediterranean Deep Water; and ShW, Shelf Water (a mixture of AW and WMDW).

The Alboran Sea Basin has been formed in the context of the Western Mediterranean back-arc during the Upper Oligocene-Miocene rifting (Comas *et al.*, 1999; Jolivet and Faccena, 2000), in the interior of the Gibraltar Arc (Betics-Rif orogen) during the westward migration of the Alboran Crustal Domain (Platt *et al.*, 2003). Stretching and normal faulting in the extensional phase produced continental crust thinning accompanied by several andesitic volcanic episodes (Duggen *et al.*, 2004). This region has been under compression from the Late Miocene to the present (Martínez-García *et al.*, 2013). It is characterized by the generation of a broad deformation area and strain partitioning (de Vicente *et al.*, 2008). The great variety of focal earthquake mechanisms ranging from pure thrust to strike slip and normal faulting (Stich *et al.*, 2010 and references therein) and the presence of penetrative linear structures on the seafloor evidence the intense and varied active tectonics in this region (Gràcia *et al.*, 2006; Ballesteros *et al.*, 2008; Vázquez *et al.*, 2008).

The basement of the Alboran Domain has been deforled from the Tortonian to the present simultaneously the tilting of the Iberian and African continental margins and the uplift of the Betic and Rif cordilleras around the Alboran basin – Betics and Rif Ranges. Cordilleras uplift and the reduction and deepening of the Tortonian basin must be considered as part of the same deformation process related to the overall convergence between Africa and Eurasia and the blocking of the Alboran Domain westward migration. The Betics Cordillera uplift is evidenced by the presence of Tortonian carbonate reefs at 1,000 m in elevation (Braga *et al.*, 2003) and by current GPS measurements series (Giménez *et al.*, 2000). As a result, the Messinian saw the closure of the rifean and north betics straits which constituted the connection between the Atlantic Ocean and the Mediterranean Sea. This closure resulted in partial desiccation of the Mediterranean Sea and intense erosion of their margins (CIESM, 2007; Estrada *et al.*, 2011). Later, Pliocene and Quaternary tectonics would drive the formation of the new Gibraltar connection.

Pliocene to present sedimentary regimen of the Alboran Sea Basin is controlled basically by the interplay of three processes: i) sedimentary inputs from the interlands controlled by uplift of surrounding cordilleras, ii) glacioeustatic sea level changes, iii) and water masses dynamics and their related bottom motion modulated by long term climatic oscillations and short term seasonal variations.

In recent years the interpretation of sedimentary systems throughout the Pliocene-Quaternary and current sedimentary dynamics has undergone a major change: the new sedimentary models are based on the importance of the erosion and deposition processes related to water masses dynamics and sea level changes at regional scales and to tectonically controlled morphological features at local scale (Palomino *et al.*, 2011; Ercilla *et al.*, 2012a,b; Juan *et al.*, 2012a,b; Juan *et al.*, 2014; Ercilla *et al.*, 2015). The continental slopes mostly comprise alongslope plastered drifts with striking terraces formed under the action of the LD (Iberian margin) and HD water masses (African margin). The plastered drifts connect to a deeper plastered drift on the Western Spanish base of slope and to sheeted drifts in the basins, all formed under the action of the HD waters.

In this scenario, submarine canyons are the feeding element of the sedimentary model, as they cross the continental slope eroding the terraces and the alongslope plastered drifts and mouth directly into fan lobes on the base of the slope and in adjacent basins, with aggrading and migrating leveed channels interrupting the lateral continuity of the plastered and sheeted drifts. The canyon-fanlobe abrupt transition is always coincident with features sculpted by contour currents. Several incisive submarine canyons systems have been developed along the Pliocene-Quaternary (Estrada *et al.*, 1997; Fernández-Puga *et al.*, 1999; Estrada *et al.*, 2011) and some of them nowadays cut the Iberian margin of the Alboran Sea (Alonso and Ercilla, 2002; García *et al.*, 2006) and both flanks of the Alboran Ridge (Bárcenas *et al.*, 2004), while only one well developed submarine canyon occurs on the African margins (Ercilla *et al.*, 2002). This distribution points to a more important development of turbidity flows in the northern margins of the Alborán Sea. This work, presents a comparative morphosedimentary study of the canyons in this region.

Methodology

This paper is based on the study of combined data obtained by means of multibeam sounders (Kongsberg-Simrad EM-12S, EM-120, EM300, EM710 and ATLAS Hydrosweep DS), ultra-high (parametric TOPAS PS 018 echo sounder and ATLAS Parasound P-35) and high reflection seismic systems (EG&G sparker and 3-channel Airgun) and SIGEOF databases. All the seismic profiles were integrated into a Kingdom Suite project, comprising single and multichannel seismic records with different resolutions.

A systematic analysis has been done related to the morphography of submarine canyons using geographic information systems (ArcGis software). Their location and a series of geometric parameters were considered: head and mouth depths, average and thalweg lengths, width, incision, sinuosity and slope gradients. Where the thalweg length is measured along the current canyon axis, the average length is measured as the straight line between the head and the mouth of the canyon, sinuosity is calculated as the ratio between the thalweg and the average lengths, the width is the distance between the two main walls of the canyon, and the incision is the maximum height difference between the walls and the thalweg of the canyon.

Sampling by gravity cores and/or surficial dredges has been carried out on several canyons and a benthic TV camera (IEO VOR APHIA) was used to observe sea floor on the canyons of La Linea and Guadiaro by means of several video-transects.

Modern Submarine Canyons and Gullies Systems

The distribution of submarine canyons in the Alboran Sea shows an important difference from a morpho-sedimentary point of view: the uneven development of canyon-fan systems along the margins of this basin. Ten canyons and two gullies systems are defined in the Iberian margin (Alonso and Ercilla, 2002; Baro *et al.*, 2012), and numerous gullies with at least two canyons are described in the flanks of the Northern Alboran Ridge (Vázquez *et al.*, 2015). In contrast no main canyons and turbidite systems develop in the Moroccan margin, where the Ceuta canyon is the only submarine feature incising the slope, eroding the contourite deposits and mouthing into the entrance floor of the Strait of Gibraltar (Ercilla *et al.*, 2002) (Fig. 3). Canyons and channels define nine turbidite systems showing two main types of sedimentary models: i) submarine fan type (La Linea, Guadiaro, Baños, Torre Nueva, Fuengirola, Sacratif, Almeria) and ii) submarine ramp (Salobreña and Calahonda) type (Ercilla *et al.*, 2014; Macías *et al.*, 2015). The uneven development of Canyon-fan systems on the two margins and the variable architecture of the fans are a result of the unequal interaction between alongslope and downslope processes.

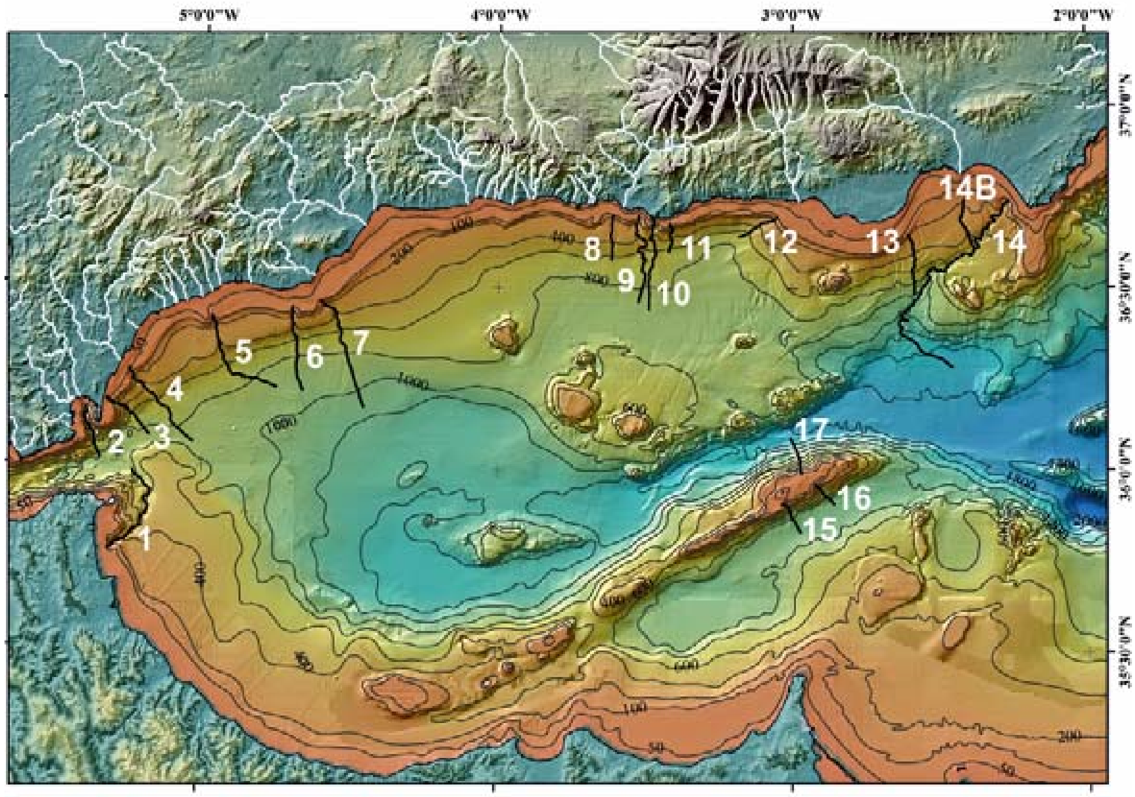


Figure 3. Location of Submarine Canyons and Gullies on the Alboran Sea margins and Northern Alboran Ridge. The fluvial drainage pattern is represented by white lines on the south-iberian onshore. 1, Ceuta Canyon; 2, Algeciras Canyon; 3, La Linea Canyon-Fan; 4, Guadiaro Canyon-Fan; 5, Baños Canyon-Fan (also called Placer de las Bovedas Canyon); 6, Torrenueva Canyon-Fan (also called Calahonda Canyon); 7, Fuengirola Canyon-Fan; 8, Salobreña turbiditic ramp system; 9, Motril Canyon; 10, Carchuna Canyon; 11, Calahonda turbiditic system; 12, Adra Valley; 13, Campo de Dalias gullies; 14, Almeria turbiditic system; 15, Al-Borani Canyon-Fan System; 16, Piedra Escuela Canyon; 17, Castor gullies area.

The sedimentary model of the fans is similar for all, being characterized by a single feeder canyon that usually crosses the terraced plastered drift of the continental slope and directly mouths into a fanlobe that develops from the lower scarp on the base of slope and basin transition. However a double canyon system feeds the Sacratif fan deposits (Alonso and Ercilla, 2002) and the Almería Canyon is characterized by a complex feeder system and a structural control (Cronin, 1995). The fanlobes comprise a single linear to low sinuosity feeder channel, which evolves to higher sinuousity channel. The fan turbidite model also comprises gullies mouthing onto a non-channel lobe. The ramp shape model comprises few to several input points represented by canyons and gullies that evolve downslope to a fan lobe with multiple leveed channels and distributary channels.

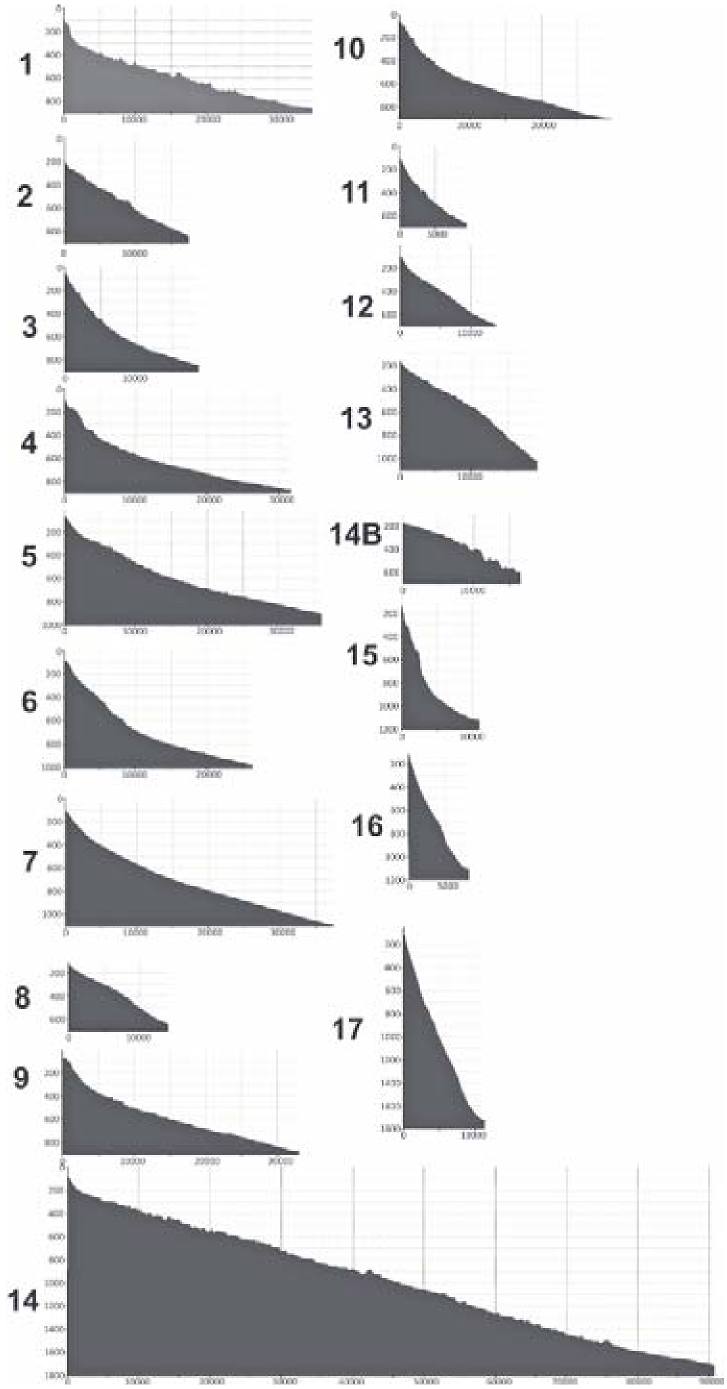


Figure 4. Longitudinal profiles of submarine canyons and gullies studied on the Alboran Sea. The profiles are located in Fig. 3.

Canyons Morphology

The following paragraphs describe the morphological features of these canyons, and the related turbidite fan (Fig. 3).

1) The Ceuta Canyon (1 in Figs. 3 and 4) is the only canyon present in the north African continental margin. It has been excavated on contourite deposits that form the Ceuta plastered Drift (Ercilla *et al.*, 2002). It has a length exceeding 40 km, a width between 3 and 6 km and a marked pathway. It extends from 55 m water depth at the head to 900 m water depth, mouthing on to the floor of the Strait of Gibraltar where accumulation of related deposit has been mapped.

2) The Algeciras Canyon (2 in Figs. 3 and 4) is located in the axis of the Algeciras Bay. It has a length greater than 20 km and a winding track. Its width varies between 1 and 4 km, and it extends from 24 m water depth at the head and 864 m water depth at the mouth, also located on the floor of the Strait of Gibraltar without related deposits. Its head is close to the coast (< 1 km) that is off the mouth of three rivers in the central part of the bay: Palmones, Guadacortes, and Guadarranque rivers.

3) La Linea Canyon-Fan (3 in Figs. 3 and 4) is the smallest of these systems located on the Alboran Sea (< 20 km long, < 8 km wide). It is fed by a main canyon and a secondary tributary canyon that merges at the foot of the lower slope. The eastern secondary canyon is about 7 km long, its head is located at the upper slope related and corresponds to a landsline scar whereas the western main canyon (9 km long) incises into 2 km the outer shelf and has a width between 1.4 and 1.9 km. Its head is characterized by two gullies that together have a horseshoe geometry whose branches are opened towards the coast and join to the canyon thalweg. These gullies begin their development at 15 m water depth, no more than 1 km distant from the coast, without apparent connection with any river mouth, and are 1.5 and 2 km long. Canyons mouth onto a fan shape lobe which is incised by rectilinear channels (< 5 km long).

4) The *Guadiaro Canyon-Fan* (4 in Figs. 3 and 4) is about 25 km long and 16 km wide. It is defined by a 14 km long feeder submarine canyon, and 1.7-2.5 rim width, whose head incises 3.5 km onto the outer shelf and is controlled by a rock outcrop. It is located 3 km from shore characterized by the mouth of the Guadiaro river. The canyon evolves to a lobe incised by a unique 13 km long leveed channel whose dimensions decrease downslope. The lobe has a fan shape 14 km long and 16 km wide; its seafloor morphology reveals the presence of old channels in the distal domains. A pockmark like feature field has been located on these deposits.

5) The *Baños Canyon-Fan* (5 in Figs. 3 and 4) is about 35 km long and 13 km wide. It comprises a 17 km long submarine canyon with 0.6-1.8 rim width (also called Placer de las Bovedas Canyon) whose head incises onto the outer shelf about 2 km. The head is located to the east of a rocky outcrop and the distance to the shore is about 6 km, where some rivers mouth as Guadalmina o Verde are found, without a direct relationship. The canyon evolves to a 6 km long leveed channel with a sinuous pathway. This leveed channel evolves to a channeled lobe that bifurcates into smaller distributary channels. The fan lobe displays a lobate shape area 16 km long and 12 km wide.

6) The *Torrenueva Canyon-Fan* (6 in Figs. 3 and 4) is 37 km long and 6 km wide. It is characterized by a canyon (also called Calahonda Canyon) about 15 km long and 0.5-2 km of rim width. The head incises 2 km onto the outer shelf and is located at 5.5 km from the shore where no main river mouth is found. At the depth of 600 m it is characterized by a strong linear geometry. This canyon evolves to a rectilinear leveed channel of 11 km long, it changes at about 1000 m water depth to a less incised and amalgamated type channel down to 1185 m water depth. There, it passes downslope to a 12 km long and 7km wide lobe. The surface of this lobe is characterized by longitudinal straight lineations that resemble small-scale rectilinear channel incisions.

7) The *Fuengirola Canyon-Fan* (7 in Figs. 3 and 4) is about 40 km long and 20 km wide. It is defined by a 14 km long and narrow (0.7 km wide) canyon, whose head enters onto the shelf about 1 km. It is located 6 km away from the coast and the river Fuengirola of the mouth. It evolves to a 8 km long, sinuous main leveed channel that mouths into a lobe with rectilinear distributary leveed channels. The fan lobe deposits have dimension of about 25 x 19 km.

8) The *Salobreña turbiditic ramp system* (8 in Figs. 3 and 4) is defined by two major gullies (about 14 km long), and three more between these (3 to 8 km long), with the head located on the upper slope around 180-190 m water depth. However they must be related with a group of very straight and small-scale gullies, at least twenty, that cross the outer shelf and the shelf break and have lengths between 0.5 and 2 km, directly related to the submarine deltaic deposits of the Guadalfeo river. Feeding gullies mouth into a lobe with an unchanneled apron shape about 17 x 11 km.

9) The *Sacratif turbiditic system* is fed by two canyons, eastern or *Motril Canyon* (9 in Figs. 3 and 4) of 9 km long and 2.4-3.5 km rim wide, and western or *Carchuna Canyon* (10 in Fig. 3A) of 11 km long and 2-3.2 km rim wide. The head of the Motril Canyon enters 1.5 km in the outer shelf and one additional km corresponding to a narrow gully which has 15 m of incision and extends toward the coast close to the submarine deltaic deposits of the Guadalfeo river. The head of the Carchuna Canyon incises 3.3 km onto the inner shelf, and it reaches 15 m water depth. It is located very close to the coast (< 0.5 km) without any rivers mouth. Both canyons evolve to leveed channels < 7 km long that mouth into channeled lobes with distributary channels that have variable pathways, from sinuous to reclinear. The lobe has dimensions of 24 x 14 km.

10) The *Calahonda turbiditic ramp system* (11 in Figs. 3 and 4) is composed of at least four relatively short (1 to 6 km long; 0.6-0.8 km wide) canyons plus gullies, their incision and length decrease to the east. These canyons evolved to leveed channels up to 11 km long, with trajectories from rectilinear to low sinuous. All together define a channeled lobe with an apron shape of 15 x15 km.

11) The *Adra Valley* (12 in Figs. 3 and 4) is a smooth valley channelized in the thalweg. It is 11 km long and 0.4-0.8 km wide. It has a slightly curved geometry and is extended from 85 m water depth in the head, at 6 km of distance from the Adra river mouth, until 650 m water depth where the canyon mouth on the Motril basin floor without related deposits. Its path is conditioned by a NE-SW active Quaternary anticlinal (Vázquez *et al.*, 2014).

12) The *Almeria turbiditic system* (14 in Figs. 3 and 4) is the largest turbiditic system of the Alboran Sea. The course of the Almeria Canyon is affected by the Serrata and Cape of Gata faults and by the interaction with NNE–SSW structures at several points along its longitudinal extension (Estrada *et al.*, 1997; Lo Iacono *et al.*, 2008). The canyon head is NE-SW oriented, it is located 3.5 km from the shore, close to the Cape of Gata, and entering about 4 km onto the shelf. The canyon is fed by three additional tributary systems (García *et al.*, 2006): the first is named Campo de Dalias which corresponds to a set of NNW-SSE to N-S oriented gullies (13 in Figs. 3 and 4) of 9 to 22 km, long occasionally with NNE-SSW oriented segments related to the action of main faults; the second is the Andarax system that is NNW-SSE oriented and shows two well differentiated sectors dissected by the La Serrata fault, northwards corresponding to a set of gullies related to the submarine deltaic deposits of the Andarax river mouth and soutwards corresponding to a major canyon; and the third, named Gata, corresponds to a NNE-SSW oriented channel generated by binding of the gullies that are eroding the shelf break and upper slope of the western part of the Cabo de Gata shelf. The Almeria Canyon at 1200 m water depth evolves to the fan lobe formed by the Almeria leveed Channel that runs southward for 26 km describing a curve trajectory down to about 1650 m. When this channel enters the eastern Alboran basin (about 1500 m water depth) the overbank area widens and from 1650 m the main leveed channel branches into distributary channels that make up the lobe deposits that extend down to the seafloor at 1800 m water depth. The fanlobe has the biggest lobular shape, 45 km long and 30 km wide.

13) The *Al-Borani Canyon-Fan System* (15 in Figs. 3 and 4) is located on the southern flank of the Northern Alboran Ridge. The Al-Borani canyon extends from the shelf (65–120 m water depth) downslope to 800m water depth (lower slope), with an average gradient of 12°, 3 km long and 2-2.5 km wide. The head zone is located around 65-70 m water depth and is characterized by several scars that produce a horseshoe geometry open to the canyon and affect the insular shelf of the Alboran Island. This canyon largely corresponds (1.8 km) to the proper incision on the Alboran island shelf. The upper canyon sector (110–350m depth) trends WNW–ESE and contains most of the tributary gullies. The lower canyon (350–800 m depth) is oriented NNE–SSW and becomes steeper (up to 19°) around 700 m water depth. Depositional features are located at the base of the slope-basin floor, where the Al-Borani Fan occurs. This fan is lobate, with a maximum width of 7 km and a length of about 7.7 km, and extends from 800 to 1,100 m water depth with a gentler gradient (1°–4°). It has two main NNW–SSE turbidite channels, small distributary channels, overbank deposits, and lobe deposits (Macías *et al.*, 2015).

14) The *Piedra Escuela Canyon* (16 in Figs. 3 and 4) is located on the southern flank of the Northern Alboran Ridge. It extends from 106 to 935 m water depth, is 5.7 km long and 0.5-0.9 km wide, and incises 0.9 km onto the Alboran island shelf. A mass flow deposits extends to 1115 m water depth from its mouth on the Southern Alboran Basin, it has 4.5 km long and 4 km wide, but no channels have been differentiated.

15) The *Castor gullies area* (17 in Figs. 3 and 4) is located on the northern flank of the Northern Alboran Ridge. It is composed by the Castor Canyon (10 km long, 0.4-0.6 km wide) that incises 1 km onto the outer shelf of the Alboran Island and connects the top of the North Alboran Ridge with the floor of the Alboran Trough, and over gullies (3-4.5 km long). No recognized deposits are associated with this system.

The distribution of submarine canyons in the Alboran Sea shows an important difference from a morpho-sedimentary point of view: the uneven development of canyon-fan systems along the margins of this basin. Twelve submarine canyons, gullies sets or canyon-fan systems (15 to 99 km long) have been identified in the Iberian margin and three minor canyon-fan system (4-8 km long) or gullies set have been localized in the flanks of the Northern Alboran Ridge (Fig. 3). In contrast, Canyon-fan systems do not develop in the Moroccan margin, where the Ceuta canyon is the only submarine feature incising the slope. The uneven development of Canyon-fan systems on the two margins and the variable architecture of the fans are a result of the unequal interaction between alongslope and downslope processes.

Modern habitats and sediments

At present no systematic study of bottom types and habitats has been carried along the Alboran Sea submarine canyons and gullies (Würtz, 2013), except for a multidisciplinary oceanographic survey realized in the frame of the VIATAR Project (Díaz-del-Río *et al.*, 2014) to characterize the sediments and habitats along two canyons-fan systems in the northwestern area of the Alboran Sea, the La Linea and Guadiaro canyons and fan deposits (Fig. 5).

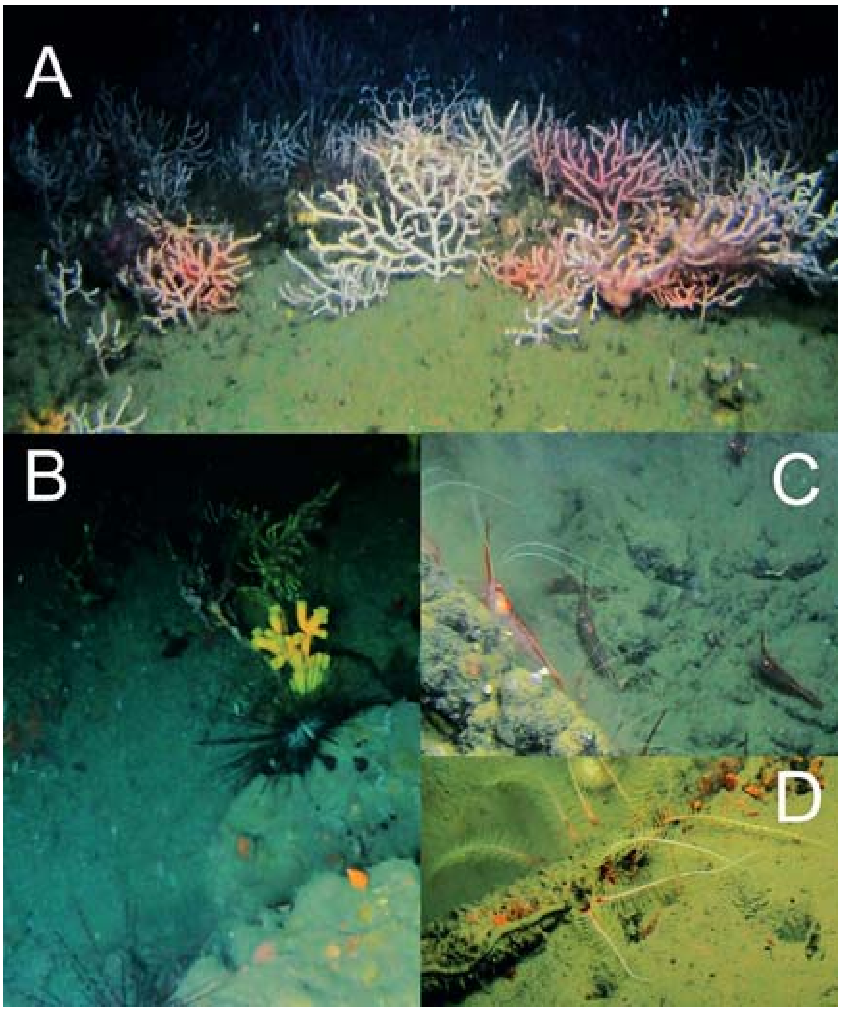


Figure 5. Different habitats and species found in La Linea and Guadiaro submarine canyons (Northwestern sector of the Alboran Sea). (a): Aggregation of gorgonians (*Eunicella verrucosa*); (b): Detail of two threatened species the sea urchin *Centrostephanus longispinus* and the cold-water coral *Dendrophyllia cornigera* (yellow); (c): Crustacean decapods of the genus *Plesionika*; (d): The ophiuroid *Ophiothrix* sp.

A) La Línea Submarine canyon

The seafloor of the head canyon (100-140 m depth) is characterized by muddy fine sand sediment, with abundant detritus, and a benthic community dominated by filter and deposit feeders, including sea-pens, sedentary polychaetes (Onuphidae, *Spiochaetopterus* sp.), molluscs (*Tellina compressa, Euspira fusca,* etc.) and decapods such as *Goneplax rhomboides* and pagurids (*Pagurus* spp.). This type of benthic community is somehow similar to the so called "Biocoenose des vases terrigenes cotieres" by Pérès and Picard (1964), included in the EUNIS habitat type "Circalittoral sandy mud" (A5.34). At this depth, there are also hard bottoms at the walls of the head, especially at the central part of the two tributaries where abundant remains of cold-water corals (mainly *Madrepora oculata*) occur as well as some echinoderms inhabiting the crevices among them (mainly *Ophiothrix* cf. *fragilis*). Live coral of the genera *Caryophyllia* and *Coenocyathus* colonize the vertical sides of the rocks. These formations with hard bottoms colonized by cold-water corals are included in the EU Habitat Directive (Reefs 1170), in the OSPAR convention ("*Coral gardens*") and also in EUNIS ("*Circalittoral coral reefs*", A5.63).

At 200 m depth, the thalweg sediment contains a higher amount of bioclasts (mainly remains of bivalves and of *M. oculata*) and the associated species include some decapods such as *Plesionika* *martia* and pagurids (*Pagurus* sp.), as well as sedentary polychaetes (*Spiochaetopteridae, Cirratulidae*) and macrourid fishes (*Malacocephalus laevis*). At the margins of the channel, the hard bottoms contain a higher density of ophiuroids (mainly *Ophiotrix* cf. *fragilis*) as well as solitary (*Caryophyllia* sp.,) and colonial cold-water corals (*M. oculata, Dendrophyllia cornigera*), constituting a habitat that is also in the Habitat Directive (*Reefs* 1770) and similar to the listed OSPAR and EUNIS habitats constituted by cold-water corals. Other species with a protected status included in the Annex II of the Barcelona Convention such as the gastropod *Charonia lampas* subsp. *lampas* also occur in this area.

At the thalweg of the canyon from 300 to 400 m water depth the sediment is composed of muddy fine sand. At 300 m water depth the thalweg is colonized by cerianthiids (*Cerianthus* sp.), decapods (*Pagurus* spp. and *Munida* spp.) and echinoderms (*Cidaris cidaris*) with a higher amount of cold-water coral remains (*M. oculata*) in those areas located close to the sides of the channel. At 400 m depth, sediments have a higher percentage of recent bioclasts of typical infralittoral mollucs (*C. gallina, Glycymeris nummaria*) as a consequence of the downward transport. The benthic community is dominated by different polychaete groups (mainly Eunicidae, Glyceridae and Capitellidae), molluscs species (*T. compressa, Nassarius ovoideus* and *E. fusca*) and the sea-cucumber *Leptosynapta* cf. *inhaerens*. Some of these species are very common in shallower circalittoral bottoms with muddy fine sand, and their presence could also be linked to the transport from the shelf down the canyon. This hypothesis is supported by the finding of large remains of leaves of the Mediterranean endemic seagrass *Posidonia oceanica*, which constitutes meadows in infralittoral bottoms located nearby (e.g. Manilva) (Luque and Templado, 2004). At greater depth (425m), the sediment is muddy with abundant detritus and remains of typical shelf species, such as the bivalves *Saccella commutata* and *Myrtea spinifera* as well as the gastropod *N. ovoideus*. The benthic community has a lower biodiversity than that at the upper parts of the canyon and is dominated by small capitellid polychaetes. At the eastern side of the thalweg, between 310-440 m, the sediment is muddy and colonized by cerianthiids, with the presence of the decapods *Munida* sp. and *Plesionika* sp. and a higher amount of cold-water coral remains close to hard bottoms on the side of the thalweg. In this area the two main types of habitats are the “Deep-sea biogenic gravels” (EUNIS A6.22) and the “Deep-sea mud” (EUNIS A6.5). At greater depths (800 m), the sediment is similar as well as the habitat type, which is dominated by cerianthiids, with the presence of disperse echinoids (mainly *Cidaris cidaris*).

B) Guadiaro submarine canyon

At the head of the canyon (~ 70-90m), the sediment is composed of pebbles, and microgravels coarse sand and mud, and the benthic community contains species typical of these sediment types on the continental shelf of the Alboran sea, such as the bivalve *Astarte fusca* or the echinoid *Echinus acutus*. This type of community usually appears in the EUNIS habitat “Circalittoral mixed sediments” (A5.44). At greater depths the sediment is also characterized by bioclasts (remains of corals, shells) as well as rocks of different sizes. The gorgonian *Eunicella verrucosa* is very common on these bottoms, along with species such as the echiuran *Bonellia viridis* or echinoderms *Echinus acutus* and *Centrostephanus longispinus*. The last species is protected under the Habitats Directive 92/43/CE (Annex IV) and is listed in the annex II of the list of endangered and threatened species of the Barcelona Convention. This type of habitat is included in the Habitat Directive (1170, “Reefs”), in OSPAR convention (“*Coral gardens”*) and represents the EUNIS habitat type “Mediterranean coralligenous communities moderately exposed to hydrodynamic action” (A4.26).

At the middle-upper part of the canyon (233 m depth), the sediment has a lower content of pebbles, and bioclasting gravels and a higher presence of compact mud. The benthic community is composed of polychaetes such as *Spiochaetopterus* sp. and molluscs such as *Anadara polii* and *Clelandella miliaris*. The benthic community is composed of *Plesionika* cf *edwarsii*, galatheid crabs (mainly *Munida* sp.), echinoderms (*Echinus acutus*), gorgonians (mainly *Callogorgia verticillata*) and large colonies of the cold-water coral *Madrepora oculata*, with larger densities than those found at La Linea submarine canyon. The cold-water coral habitats are included in the EU Habitat Directive (Reefs 1170), in the OSPAR convention (“*Coral gardens”*) and also in EUNIS (Circalittoral coral reefs, A5.63). At greater depths (293 m) sediments are composed of fine sand with sparse rocks of different sizes and medium levels of bioturbation. This area displays a lower biodiversity, with the presence of the decapod *Plesionika* sp., the crinoid *Neocomatella europaea,* and the ophiuroid *Ophiotrix* sp, among the rocks. At greater depths along the thalweg (397m) muddy bottoms are dominant and colonized by polychaetes of different families (Capitellidae, Terebellidae, Spionidae, Polynoinae) and typical shelf bivalve molluscs such as *S. commutata* or *M. spinifera*. The habitat would correspond to "Deep-sea mud" (EUNIS A6.5); it also contains benthic components that would normally occur at shallower depths but could have colonized these bottoms due to the vertical transport of sediment and fauna along the canyon.

Geohazards

Two main processes related to canyon occurrence have been detected as probable hazards in the Iberian margin of the Alboran Sea:

i) The development of landslides along the canyon leading to tsunami triggering in the basin. Landslides have been located on the upper slope sector of the La Linea and Motril canyons, and at the canyon head of the Alborani canyon (see Macías *et al.*, 2015).

ii) Retrogressive erosion at the canyon head have been detected in several canyons; the most important is related to the Carchuna canyon (Ortega *et al.*, 2014) the highest economic impact could be produced at the Algeciras canyon head where substantial human infrastructures are located. Other areas affect by gullies erosion are the head of the Motril and La Linea canyons.

Canyon-fan systems evolution

The architectural elements of the canyon-fan systems show different seismic facies. The canyon fill deposits display complex facies pattern with chaotic fill, prograding fill, divergent fill and mounded fill facies. Canyon facies are better developed in the Fuengriola and Almeria canyons. Some canyons (Baños/Calahonda and Torrenueva) do not show canyon floor deposits and their seismic expression is only recognized by the V-shape valley incision with truncation of reflections in their walls and floors. The canyons facies appear as irregular bodies with a well-defined distribution related to the linear canyon feature. The channel fill deposits, that are similar to the canyon ones, are defined because of their association to the levee deposits and are mostly defined by chaotic facies. They are identified in all the turbiditic systems. The chaotic facies presents two subtypes: i) wavy and disrupted reflections of medium amplitude that appear as mound or lens-shaped bodies, bounded by irregular erosional surfaces; and ii) strong, contorted reflections of high acoustic amplitude with hyperbolic and hummocky reflectors, sometimes showing traces of the original parallel bedding. Their overbank deposits are formed by downlapping continuous conformable to wedging reflections. The lobes display facies that vary laterally, being mostly chaotic and/or transparent for the distributary channels, and stratified, continuous and discontinuous, for the overbank, non-channeled and lobe fringe.

Discussion and conclusions

The Alboran Sea is characterized by at least fifteen erosive systems, between submarine canyons, valleys, gullies and channels, which are the main feeder system of at least nine turbiditic fans in the Iberian margins and two in the Northern Alboran Ridge but none in the African margins.

Main controls of submarine canyons evolution and distribution are related to regional tectonics, water mass dynamics and sea level fluctuations linked to climate oscillations. Recent findings indicate that most of the canyons described here originate from at least the Messinian salinity crisis. Formation and/or location of Alboran canyons have been related to connection of river mouths (e.g., La Linea, Guadiaro), retrogradational local slope failures (e.g., Baños, Torrenueva). Sediment source has been mainly controlled by the Pliocene-Quaternary compressive tectonics that produces the uplift of the surrounding Betic-Rif cordilleras and basin inversion (Martínez-García et al., 2013). Deformation controls the continental sediment input provided by river transport as well as the accommodation of the sedimentary units. When sediment arrives to the sea, water masses circulation redistributed it throughout basin or formed dense gravitative flows that are funneled down through the canyons . There suspended sediment interferes with contemporaneous secondary circulation through the canyons (Allen and Durrie de Madron, 2009; Allen and Hickey, 2010). Likewise, reworking shelf sediment by storms and carving canyons walls and floor can also supply additional sediment to the flows running along canyon (Ercilla *et al.*, 1994; Alonso and Ercilla, 2002; Fernández-Salas, 2007). In the northwestern canyons, a well differentiated alonslope influence is noted along the entire canyon-fan system: the eastward AW influences the canyon head, the westward Mediterranean LW interferes along the main canyon course and the Mediterranean HW affect the fan deposit. A similar pattern is observed in the northeastern area.

Finally, the influence of climatic oscillations has a twofold dimension on the dynamics of submarine canyons. On the long term, the Pliocene-Quaternary glaciations episodes, have been commonly used to explain the episodes of canyons enlargement, excavation and incision of the continental shelves during events of sea level falls (Ercilla *et al.*, 1992, 1994; Hernández-Molina *et al.*, 1994; Ercilla and Alonso, 1996; Hernández-Molina *et al.*, 2002; Ortega *et al.*, 2014). The pattern of this incision is slightly regular, usually reaching the head between 55 and 90 m water depth, at distances less than 1 km from the coast. With respect to short-term variations, we suggest fluvial flooding events and / or to rapid increases in rivers flow as a main factor controlling sedimentary and evolutive dynamics. These processes can generate hyperpycnal flows at the rivers mouth that sink due to its higher density, and can cross the continental shelf and reach the canyons head, producing both erosive and sedimentary effects on the continental shelf (gullies and sedimentary waves) and along the canyons (gullies and turbiditic events). These processes have been observed mainly in the central and eastern sectors of the margin related to the mouth of Guadalfeo, Adra (Fernández-Salas *et al.*, 2007; Lobo *et al.*, 2006; Lobo *et al.*, 2014; Bárcenas *et al.*, 2015) and Andarax rivers.

The sedimentary development of these canyons-fans systems suggests that the spatial and temporal distributions of the turbidite deposits making up these fanlobes involve lateral and longitudinal migrations of the main turbidity flows and related flows coming from the canyons. The relocation of flows pathways have been analysed in detail for the Sacratif system. Likewise, the development of these canyons-fans systems interrupts the lateral continuity of terraced plastered and sheeted drifts. The depositional architecture, dimensions, and plan-view morphology of the canyon-fan elements indicates that the sedimentary composition of the fans ranges from sandy to mixed sand-mud, becoming sandier towards the Strait of Gibraltar.

The oceanographic gateway context of interaction between Atlantic and Mediterranean waters that characterizes the Alboran Sea and its related bottom contouritic processes, is also a main factor responsible for the architecture model of these canyon-fan systems as well as their absence in the Moroccan margin (Ercilla *et al.*, 2014). When fine sediment arrives to the sea, it is taken by the Atlantic water mass (0 to 250 m depth) and distributed by the two anticyclone gyres that define its circulation. Fine sediment becomes part of a complex system of circulation mainly formed by three underlying water masses, the Winter Intermediate Water (100 to 300 m), the Levantine Intermediate Water (200 to 600 m) in the Spanish margin, and the Western Mediterranean Deep Water (> 275 m) mainly in the Moroccan margin. Their contouritic processes contribute to the outbuilding of the margin and infilling of the basins.

Based on the oceanographic and sedimentary contexts, as well as the overall architecture and geometry of the canyon-turbidite systems, it is possible to distinguish two scenarios where there is interaction between alongslope and downslope processes, occurring at different intensities. These scenarios help us understand the potential mechanisms that may have been conditioning the uneven development of canyon-fan systems in the Alboran Sea basin (Ercilla *et al.*, 2014).

1) *The Spanish margin scenario, where the interaction has conditioned the fan architecture and its variability.* In this scenario when sediment arrives to the sea, the finest fraction is capted by the AW. The dynamics of the two anticyclone gyres and the well-developed isopycnal and related processes (e.g., internal waves) between the Atlantic and Mediterranean waters represent potential mechanisms for maintaining the fine sediment in suspension and dispersing it in the nepheloid layer throughout the Alboran Sea. Caption would result in fine sediment deprivation in the downslope flows feeding the fans, explaining the lack of defined levees in the canyon margins and the sandier fans towards the Straits of Gibraltar, where the currents are faster. Thus, the interplay between the unequal activity of the AW (its eastwards velocity decrease) and its two

anticyclonic gyres (Eastern-permanent versus Western-semipermanent), as well as the LD and HD accelerating toward the Strait of Gibraltar, would favour significant captation from the gravity flows outbuilding the fan lobes in the west.

2) *The Moroccan margin scenario, where the interaction is stronger and has conditioned the lack of canyon-fan systems.* In this scenario, the interplay between the captation by the Atlantic anticyclonic gyres, more sediment in suspension, and dispersion due to the enhanced density contrast between the AW and HD Mediterranean waters, together with the waters of the HD core impinging and accelerating along the Moroccan margin due to being forced to flow upslope, all favour intense alongslope sediment transport. This intense transport avoids the convergence of sediment along the Moroccan margin, inhibiting the local occurrence of potential erosive gravity flows and leading to the formation of canyons and/or their related fan lobes.

Acknowledgements

Funding for this research was provided by the following projects: CONTOURIBER, MONTERA, TOPOMED, MOWER, and VIATAR. This is a contribution of the Continental Margins Research Group (CMRG - 2009SGR1071, Generalitat de Catalunya), Geosciences Marine Research Group (GEMAR – IEO) and Littoral and Marine Geophysical and Geological Research Group (RNM 0328, PAIDI).

---

* this chapter is to be cited as:

Vázquez J.T., Ercilla G., Alonso B., Juan C., Rueda J.L., Palomino D., Fernández-Salas L.M., Bárcenas P., Casas D., Díaz-del-Río V., Estrada F., Farran M., García M., González E., López-González N., El Moumni B., Contouriber, Montera and Mower Teams. 2015. Submarine Canyons and related features in the Alboran Sea: continental margins and major isolated reliefs. pp. 183 - 196 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.