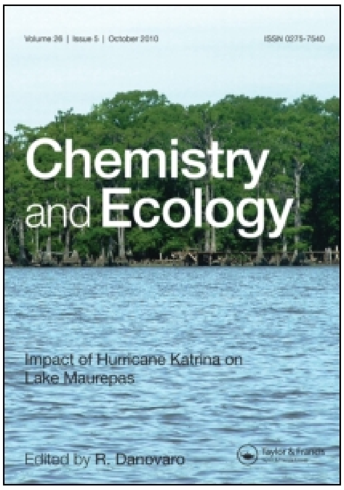

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Preliminary data concerning the morphology of a Calabrian Ionian margin area: Caulonia and Marina di Gioiosa canyons

C. Tessarolo[a]; E. Malinverno[a]; M. Agate[b]; G. Di Grigoli[b]; C. Corselli[a]
[a] Department of Geological Science and Geotechnologies, Università degli Studi Milano-Bicocca, Milano, Italy [b] Group of Marine Geology, Department of Geology and Geodesy, Università degli Studi di Palermo, Italy

To cite this Article Tessarolo, C. , Malinverno, E. , Agate, M. , Di Grigoli, G. and Corselli, C.(2008) 'Preliminary data concerning the morphology of a Calabrian Ionian margin area: Caulonia and Marina di Gioiosa canyons', Chemistry and Ecology, 24: 1, 225 — 242

To link to this Article: DOI: 10.1080/02757540801970449
URL: http://dx.doi.org/10.1080/02757540801970449

Chemistry and Ecology
Vol. 24, No. S1, June 2008, 225–242

Taylor & Francis
Taylor & Francis Group

Preliminary data concerning the morphology of a Calabrian Ionian margin area: Caulonia and Marina di Gioiosa canyons

C. Tessarolo[a]*, E. Malinverno[a], M. Agate[b], G. Di Grigoli[b] and C. Corselli[a]

[a]Department of Geological Science and Geotechnologies, Università degli Studi Milano-Bicocca, Milano, Italy; [b]Group of Marine Geology, Department of Geology and Geodesy, Università degli Studi di Palermo, Italy

(*Received 16 July 2007; final version received 20 November 2007*)

In the framework of the Vector National Italian Project (VulCost line), aimed to study the role of the morphology and the geology of the Ionian Calabrian margin in the coastline evolution, an oceanographic cruise was planned to collect geophysical data along two canyon systems: Caulonia and Marina di Gioiosa. The survey explored the continental shelf and slope from a depth of 15 m to more than 1150 m, using Multibeam Echosounder to investigate the seafloor topography. This work provides an outline of the erosive feature of the slope, shaped mostly by seasonal river input and by the connection to the structural and geological characteristics of the margin, made interesting by a narrow shelf and steep slope and influenced by a recent Quaternary tectonic, cause of the crustal regional seismicity. The collected data allowed us to perform a first characterisation of the geo-morphological peculiarities of the study area, constituting the base for the evaluation of the coastal zone evolution.

Keywords: Ionian Calabrian Margin; seafloor topography; morphology

1. Introduction

The Ionian Calabrian margin is part of a complex geo-structural setting, where the interplay between uplift-subsidence phenomena of the presently emerged portion, and the consequences of Quaternary sea-level fluctuations, represent the more influential factors for the control and characterisation of the morphologies and structures currently developed. These situations were originally linked to the tectonic movements due to the translation and uplift of the Calabrian Arc, followed and forced in their modifications by the eustatic [1–3] Quaternary variations linked to the glacial-interglacial oscillations. In fact, the Ionian side of the Calabrian margin is currently steep, characterised by quite marked relief (up to 1400 m) on areas close to the coastal zone, and by a narrow expansion of the continental shelf, with the shelf-break located very close (<7 km) to the shore limit.

In association to this structural background, the characteristic climatic regime of the region, influenced by intense but seasonal meteorological events, has promoted the development of a particular river system, on which the erosive manner seems to prevail on the depositional one.

*Corresponding author. Email: c.tessarolo@campus.unimib.it

ISSN 0275-7540 print/ISSN 1029-0370 online

DOI: 10.1080/02757540801970449
http://www.informaworld.com

These seasonal rivers are commonly named 'Fiumare' [4,5] and represent the main way through which the consistent masses of sediments are transported into the sea, affecting the iterations between emerged and submerged coastal zones.

On the basis of these assumptions, in the framework of the VulCost line of VECTOR Project, we selected four rivers which drain this part of the Ionian margin, Allaro, Amusa, Precariti, Torbido, for an evaluation of their role in the generation and modification of the two canyon systems developed in front of their outfalls: Marina di Gioiosa Canyon and Caulonia Marina Canyon, which cross the upper slope toward the Basins of Crotone and Spartivento (see Figure 1).

The study here proposed aims to demonstrate, on the basis of a detailed morpho-bathymetric survey, a preliminary geomorphological study of the Ionian Calabrian margin between the coastal town of Caulonia Marina and Marina di Gioiosa (see Figure 1 for working area geographical location), leading to the comprehension of the main geo-morphological and superficial structures currently present, and of the sedimentary processes that likely shape the continental slope. Here we described a detailed bathymetric survey that allows us to produce a morphological features chart, never published to date on this marine area.

Furthermore, this result will become the basis for a subsequent evaluation of how the bearing and the by-passing of sediments through the canyons could affect the coastal zone evolution (the final goal of the VECTOR Project in the Calabrian Ionian Margin).

1.1. *Geological setting and geographic background*

The current geo-structural setting of the Calabrian region has been determined by the interactions of intense tectonic and sea-level changes [1–3,6], which affected the whole central Mediterranean area.

This area belongs to Ionian Calabrian offshore (see Figure 1) and lies on an active continental margin, related to a type-B subduction of the Ionian slab under the Calabrian Arc. The eastward migration of the Calabrian Arc and the simultaneous opening of the Tyrrhenian Basin back-arc [7] represent the most important geodynamic process going on during the Latest Neogene–Quaternary time interval for the central Mediterranean sector.

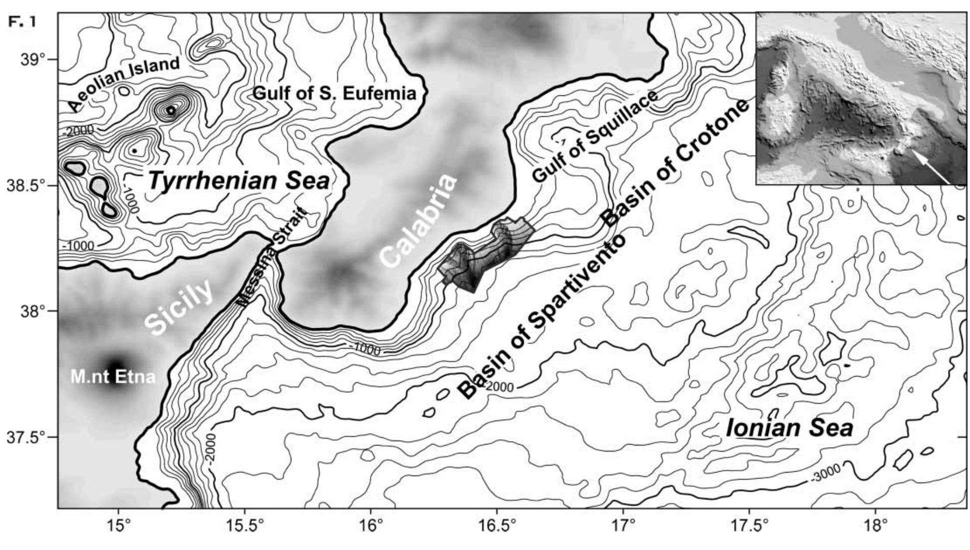

Figure 1. Location and extension of the studied area with relation to the Calabria region and the surroundings Spartivento and Crotone Basins. Bathymetric contour lines are every 200 m.

To the East, the NE-SW extension of the Ionian oceanic basin has been evaluated of Mesozoic age, based on the undulating strike of the Malta and Apulian conjugate margin [8]. The absence of an oceanic ridge would imply the abortion of a spreading ocean, with loss of the ridge topographic elevation by thermal cooling, and subsequent burial by Tertiary sediments [8].

Beginning from Late Oligocene, the Ionian basin developed along the edge of the Corsica-Sardinia-Calabria microplate, as it detached and migrated Southwestward from the Southern European plate margin [9–11], shaping from Early Miocene time toward the NNW-dipping subduction zone.

Starting from the Middle-Late Miocene, reactivation of intense tectonic movements, linked to the initial opening phase of the eastern Tyrrhenian Basin and coupled to the south-eastward migration of the Calabrian Arc, emphasised the compressive and flexural setting in the forearc sector.

The Ionian crust was consumed in a passive subduction along an inclined Benioff plane [7], causing a more intense uplift of the advancing Arc front, initially E-W oriented and partially deviated toward North East-South West for the presence of older Mesozoic extension structures (Ionian Ocean basin).

From Late Miocene, the translation-uplift of the Calabrian Arc terrain caused the opening of the Tyrrhenian sea, and shifted the Ionian basin to its present position [12].

The sedimentary deposits on the Ionian side were effected by a tilting toward East-South East, emphasizing the Pliocene transgression. This step was probably very rapid, inferred by the scarcity of shallow water and coarser Pliocene deposits, which allows the assumption that the Calabria region was mostly submerged during this Epoch.

The uplift trend started in the Early-Middle Pleistocene, affecting the Calabria and the Northeast Sicily region, progressively decreasing in intensity toward North and West [6,13,14]. This trend determined, along the inner side of the Calabrian arc, the development of normal faulting for a total length of about 180 km, with an overall ESE-WNW extension, presumably responsible for the crustal seismicity occurring in this area [15]. The individual fault segments, morphologically defined by escarpments several hundred metres high, separated the main Pliocene-Pleistocene basins from the uplifted mountain range of the Calabria region, represented by Aspromonte, Serre and Catena Costiera.

In the southern part of the arc, ENE-WSW trending fault segments show a large left-lateral component of motion, along which the extension jumps westward from the Serre-Aspromonte Mountains to the Messina Strait area, where the fault segment cut the orogenic belt of the arc.

This evidence suggests that Quaternary normal faulting could have been related to a new rifting process, rather than to the subduction-related extension, connected with the Ionian domain underplating beneath the Calabrian Arc [15]; this supports the hypothesis of a very recent tectonic activity, expressed also by the active crustal seismicity underlined by historical and instrumental earthquakes occurring since 1000 AD [15].

The extent of the Calabrian uplift, in association with Quaternary sea-level variations, has been valued in recent works, mainly by the study of deposits outcropping along the coastal zone [1–3,6,16].

Marine terraces were shaped during the sea level stands; these could take place in correspondence of the maximum and minimum climax, reached during each complete sea level variation cycle, or during a sufficient time span middle stand between the rise and the fall phases. In the Calabria region, the peculiar interaction between the glacio-eustatic oscillations of the Middle-Upper Pleistocene, 100–150 m wide for every single IV order cycle [17], and the coeval tectonic regional uplift, allows that each marine terrace, generated in a determined highstand, results at an higher quote during the subsequent highstand episode, preserving itself from the erosive action of the coastal wave motion; this situation went on for all the subsequent IV order eustatic cycles, allowing the formation of a sequence of marine terraces, exposed at different elevations along the Ionic Calabrian coast [13,18,19].

Recently, near the Messina Strait, marine abrasion terraces between 40–820 m in altitude [18], and Pleistocene terraces up to 1350 m of elevation have been found [19]; at Vibo Valentia Marina, in situ specimens of coral *Cladocora Cespitosa* have been found 50 m above the current sea level, coupled with the Last Interglacial guide fossil *Strombus Bubonius* (U-series dated at 121 ± 7 ka [20]) also found near Nocella at 157 m [13].

Consequently, the Italian peninsula cannot be considered to be tectonically stable on Quaternary (and longer) timescale: in fact it comprises about 8000 km of coastline, some of which areas are subsiding [21,22], while others, like the southern coastal zone of Calabria and eastern Sicily, are subjected to uplift, with rates reaching 1–1.4 mm yr^{-1} [1,19,23,24].

Considering the sea-level variation approach, throughout the Quaternary period the margin was affected by a series of relative sea-level rises and falls, caused by the sum of eustatic, glacio-hydro-isostatic and tectonic factors, the first with a global and time-dependent behaviour, the latter two depending on their location [2].

The glacio-hydro-isostatic part exhibits a well defined and predictable pattern, where the formulation for sea-level change could be derived from the well known growth and decay of the large high altitude ice-sheets: their effect is that the entire crust of Italy is subsiding in response to the last deglaciation [2,25].

The hydro-isostatic contribution results from the loading of the ocean floor by the meltwater entered into the Mediterranean, causing a maximum subsidence within the central parts of the basin, and relative uplift at the coasts and inland.

The tectonic component exhibits a less regular pattern, generally of shorter wavelength and less predictable, with marked differences in local evolution between adjacent coastal zones [25].

Studies dealing with detecting sea-level change since the Last Interglacial period estimate their frequency and magnitude using different indicators. The biological indicators, which represent the most used method, include two parallel approaches: the realisation of eustatic curves from benthic or planktonic foraminifera isotopic records [26–29]; and the geomorphologic analysis of marine coral terraces [30–35]. Following this method, sea level curves are inferred from the height-age relationships of raised reefs, constrained by more accurate radiometric data from corals: U-series dates from coral terraces on the Barbados and Huan Peninsular coast [36], or other U-series dates based on a stable Western Australia tectonic area [37] are commonly used for age control.

Marine terraces associated with clastic sediments are conversely seldom used to detect sea-level changes [38–45].

Recently, Dumas et al. [3] followed another approach, consisting of taking into account the thickness of marine deposits associated with these terraces: the Characteristic Thickness (CT), defined from field observations, is the pile of sediments deposited on a wave-cut platform between the break-point and the swash upper limit, whose thickness varies with sea-level oscillation and uplift. Comparing the amplitude of following sea-level fall and rise, the Authors have then defined the Vertical Difference (e) (or Eustatic Gap) between two successive marine highstands, with positive trend if sea-level fall amplitude is greater than sea-level rise amplitude. If an uplift magnitude is added to a positive eustatic gap, between two subsequent marine highstands, it increases the vertical height that separate the shorelines correspondent to these highstands; as a consequence, marine terraces are clearly stepped, and more easily observed in the field.

This assumption explains why the uplifted coast has recorded more eustatic cycles than stable areas during the Quaternary period; if (e) is negative, and greater than the sum of the uplift magnitude during sea-level fall and duration of sea-level rise, the terrace shaped during a first highstand is destroyed by the subsequent one, which shapes a new terraces, so that only younger terraces could be observed on the field (not all the eustatic cycles could be recorded in coastal landforms).

Dumas et al. [3] have evaluated sea-level fluctuations on terraces in southern Calabria, located near the Messina Strait, measuring the elevation at the inner edge of each terraces at the top of the highest observed marine deposit (with theodolite or photogrammetry based on GPS data).

In total, the Authors have identified a sequence of 23 marine terraces, with elevation between 52 and 171 m and dated approximately between 128 and 58 ka (by U-dates corals series correlation), shaped during each substage between the age control 128, 105, 83 and 58 ka, that represent the peaks of a relative sea-level maximum; the different elevation between two terraces demonstrates a different vertical amount, that proves the effects of eustatism [3].

Recently in the Crotone peninsula, Zecchin et al. [46] have evaluated the uplift of Middle Pleistocene marine terraces: they recognised five Pleistocene levels, characterised by deposits of three high-frequency cycles, interpreted as very high-frequency sea-level variations correlated to the Pleistocene oscillations of the isotopic curve.

The uplift rate inferred from the Authors' interpretation is calculated at between 0.4–1.8 mm yr^{-1}.

A less wide time span evaluation has been realised for the sea level of the whole Mediterranean Sea [25], giving some information for the last 6000 yr variations in the here proposed study area. The sea level uplift has been evaluated of about 7–8 m for the last 6000 years, and less than 2 m starting from the last 2000 years.

Lambeck and Johnston [25] have considered for this estimate the contribution of two kinds of terms: the 'ice-load term' (sea level rise as a function of deformation of the marine surface for ice cover changes), and the 'water-load term' (contribution of earth adjustment to the redistributed melt-water to the oceans). The result of this study referred to the area in exam for this work is summarised in Table 1.

Another isostatic model [47] evaluated for the Reggio Calabria zone indicates a total relative sea level rise of about 4.25 m for the last 6000 year and of 1.64 m for the last 5000 years. Even if all of these models represent an empiric mathematical evaluation of only some selected parameters, they could explain why in many sectors of the Italian peninsula, uplifted during Quaternary events, there are no clear evidences of Holocene emergences, found in Calabria at lower than expected elevation, and younger than the climatic Optimum period. On the basis of these assumptions, it is possible to affirm that during the last 6000–5000 years the tectonic uplift and the subsidence trends had have the same rate, thus compensating each other's relative effects.

If global sea-level change can be neglected, it's then only when the subsidence trend of glacio-hydro-isostatic origin became slower with respect to the local tectonic trend that a slight emergence could have begun, estimated for the last few thousand years [1].

Pirazzoli et al. [1] have observed marks of emergence over a distance of about 180 km around the South Eastern and Western coast of the Calabria region, with values from 1.0 and 1.5 m, even if only in one case (near Crotone) the emerged shoreline was actually dated from the late Holocene. This could be connected to the presence of the normal fault that crosses and dislocate in different block the Calabria region, allowing the hypothesis of more localised coseismic vertical displacement [1].

Table 1. Results of the eustatic modification evaluated in the Lambeck and Johnston study (1995) [25].

Southern Calabrian Ionian side	6000 year before	2000 year before
Ice-Load Term	3–4 m	~1 m
Water-Load Term	3–4 m	0.5 m
Ice Cover Fusion + Isostatic Land Settlement	7–8 m	<2 m

Resuming, the structural evolution on the Calabrian Ionian border determines its current configuration, interested by a very steep emerged margin (with relief up to 1400 m in proximity of the coastal zone), and by a narrow extension of the continental shelf, where the shelf break occurs sometimes at less than 7 km from the shore limit, as visible on a transect realised on the morphological data collected (Figure 2).

For what concerns the sedimentary succession present on this side of the Calabrian Arc, it is represented by Upper Pliocene–Lower Pleistocene deposits, mainly made of calcarenites which landward onlap the eastern slope of the Aspromonte-Serre mountain range, representing the margin of basins presently located in the Ionian offshore [16].

Very interesting data about the stratigraphy of the Ionian arc front have been collected within the Streamers Project, especially the lines Ion 3 and Ion 4 that run in the considered area. These profiles show the interaction between the Ionian domain and the Calabrian block: the superficial sediments, unconsolidated, develop on the frontal part of the Calabrian crustal block, interested by major thrusting revealed by the NW dipping reflectors.

On the top of this section, a deformed pile of sediments is unconformably overlain by Upper Pliocene-Pleistocene deposits that infill the large sedimentary Spartivento Basin (strike slip

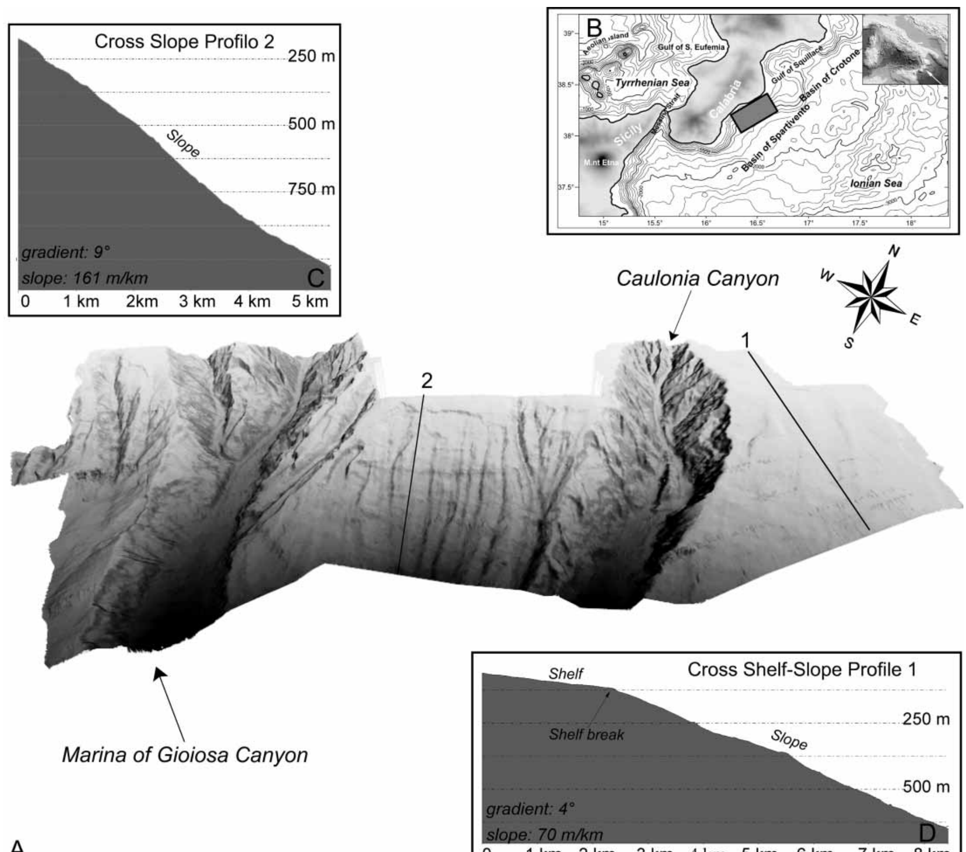

Figure 2. Shelf break profile. Traced on the central (2) and eastern (1) side of the survey area. (A) 3D view of the study area, on which are highlighted the two canyon systems: Marina di Gioiosa canyon on the left, Caulonia Marina on the right. (B) Particular of the study area location. (C) Slope of the profile 2, with gradient value pointed out ($9° - 161$ m/km). (D) Slope of the profile 1, with gradient value pointed out ($4° - 72$ m/km).

basin developed above a thick accretionary wedge, formed by several thrust sheets involving the sedimentary cover of the Ionian domain [48]).

Deeper, NW dipping reflectors, correspondent to the lower crust layer of the Ionian domain [49], mark an important flexure of the Ionian block (about 18% over a total length of 60 km).

Furthermore, the structural evolution and current activity of the area, in association with a characteristic climatic regime, emphasise a large sediment contribution in the region, delivered seasonally by the typical rivers of the Ionian Calabrian side: the ‘Fiumare’ [4,5]. This sediment supply is carried down by-passing the NNE-SSW trending upper slope, which represents the western margin of the Crotone and Spartivento intraslope Basins. Inside these basins the Plio-Quaternary clastic-hemipelagic sedimentary layers, which overlay along the margin the pre-Pliocene bed rock, are more than 1.5 s thick [50,51].

The river activity of torrents that exist on the coastal zone has determined the incision of two systems of canyon in the shelf-to-slope region, named Caulonia Marina and Marina di Gioiosa Ionica Canyon after the towns located on the coastal zone behind them, and of a variety of associated features, whose description and morphological study represent the main purpose of this preliminary work.

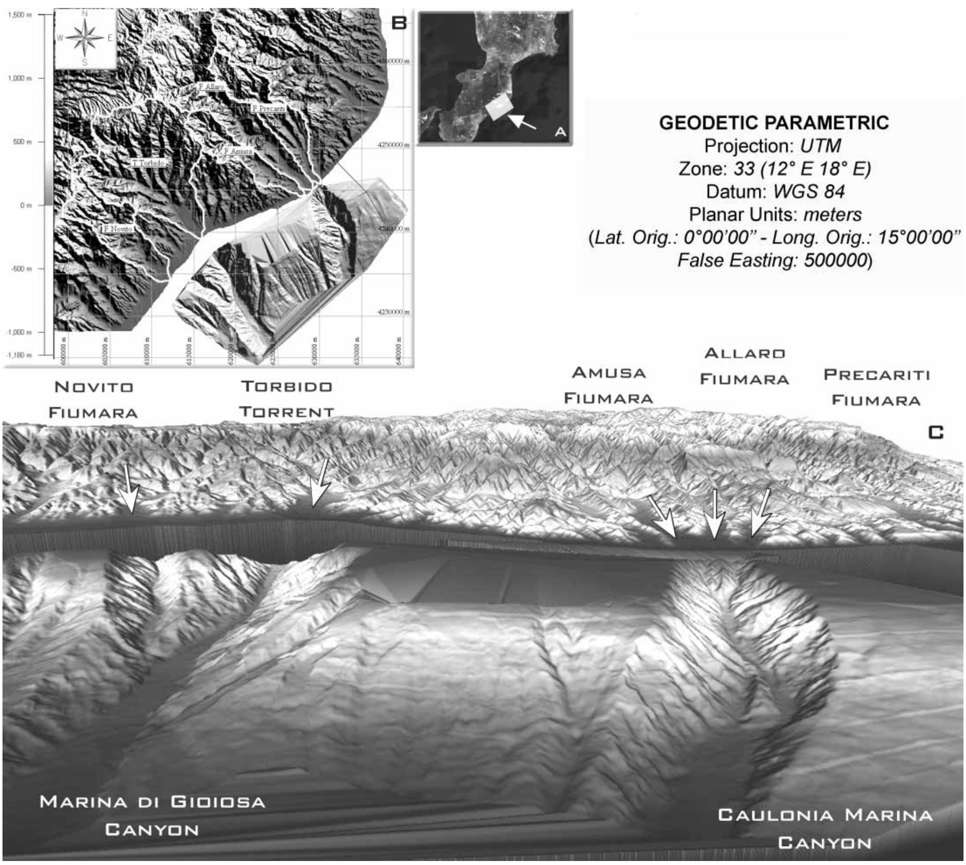

Figure 3. Elaboration of the Digital Terrain Model. (A) Particular of the study area location. (B) Planar view of the Digital Terrain Model realised for the study area and of the onshore features connected. The five rivers basins limits are visible. (C) Frontal view of the canyon systems and the connected rivers’ outfalls. The proximity of the onshore and offshore features is clearly visible.

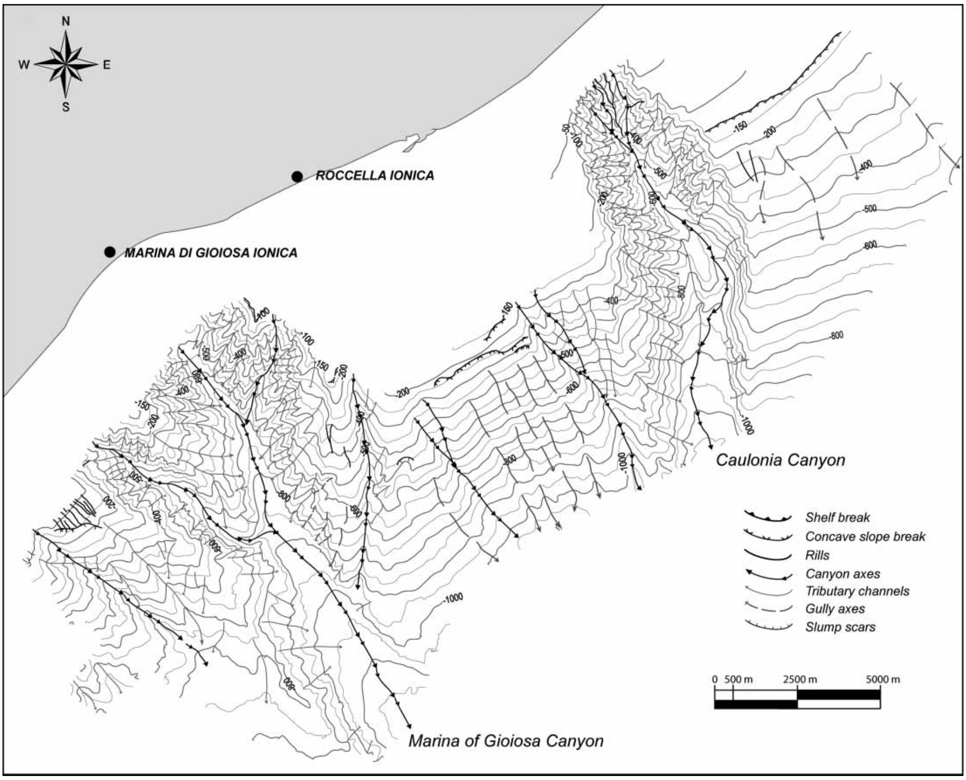

Figure 4. Particular of the Geomorphological Marine Chart with delineation of the main features identified.

2. Material and methods

The preliminary geophysical survey on the sector of shelf and slope located in front of the Allaro, Amusa, Precariti and Torbido torrents outfalls, selected within the VECTOR project, has been performed on April 2006 (02-06 April 2006) with the Oceanographic Vessel UNIVERSITATIS.

MBES Geophysical data include a series of 55 morphological survey lines (Multibeam Seabat 8160, frequency 50 kHz) variably spaced following the bathymetric contour path, and planned to realise a full coverage of the area.

The routes have been traced mostly parallel to the coastline (North East – South West), criss-crossed by two control lines, all collected with a mean vessel speed of 5–6 Knots. The investigated area, with a total extension of about 280 km^2, ranges from the shallow near-shoreline sector for about 14 km, crossing depths of 15–20 m on the shelf (more than 400 m in correspondence of the submarine incisions), and more than 1150 m at the survey limit offshore. Bathy-morphological data have been elaborated (see Appendix 1 and 2 for data acquisition and processing description) to return a detailed Digital Terrain Model (see Figure 3), having a cell size of 10 and 20 m, respectively for the shallow and deeper sector.

The principal morphological features identified by the elaboration and interpretation of the Multibeam profiles have than been delineated and mapped for the construction of the 'Geomorphological Marine Chart' shown in Figure 4.

For a better evaluation of the major canyon systems and related structures identified in the area, a series of longitudinal and transversal profiles (500 m spacing) have been traced on the DTM (Figure 5).

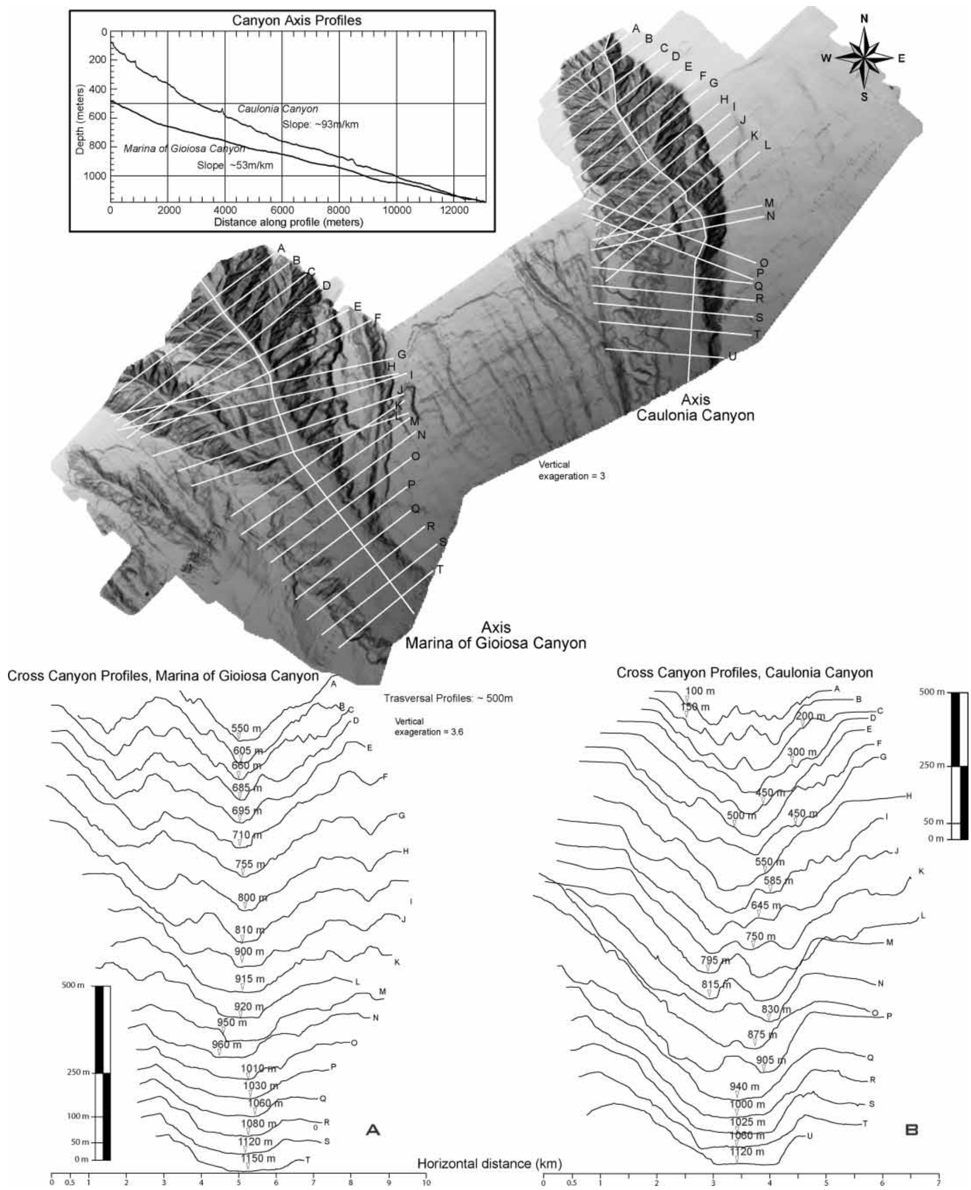

Figure 5. Upper part of the image: canyon axis profiles with gradient value indication and planar view of the 3D elaboration of the study area. The transversal profiles are indicated (every 500 m). (A) Profiles traced along and transverse to the axis of Marina di Gioiosa Canyon. (B) Profiles traced along an transverse to the axis of Caulonia Marina Canyon.

3. Results

3.1. *Results from MBES imagery analysis: the morphological features detected along the slope*

The geological-structural and environmental control presented previously have favoured a predominant erosive component in the area, linked to the amount of sediments delivered from the coastal zone and regulated by a gravitative component, acting both on the emerged and submerged areas. This situation has in fact promoted the more or less marked incision of structures, developed on very different scales, among which the most interesting are represented by the two canyon systems of Caulonia Marina and Marina di Gioiosa Ionica.

The morphological features detected through the survey will be described below.

3.2. *Canyon of Marina di Gioiosa Ionica*

The Marina di Gioiosa Canyon is located in the South Western sector of the studied area in front of the Torbido torrent outfall, whose hydrographic basin extends for about 160 km^2 [4].

The bathymetric survey performed in this location begins at a distance of about 2 km from the coastline, crossing the bathymetry of 40–50 m on the shelf, and reaching a depth of about 400 m in correspondence of the upper section of the canyon axis.

The canyon structure appears like a wide incision, characterised by a large main channel about 3 km wide that starts very close to the shore line, reaching more than 4 km at the base offshore (see Figure 5A). The thalweg develops following an approximately sigmoidal path, with the proximal and distal reach NW–SE oriented, and the middle reach N–S oriented.

The upper reaches of the canyons are interested by a developed drainage pattern, constituted by nearly parallel rills that descend downslope the canyon walls following an almost linear trend. Laterally, the structure is extended by the presence of two tributary channels, both of them with relevant size, that merge into the main channel at different depths.

The eastern lateral channel, whose survey begins at a major distance from the shore limit, is 1km wide with a N–S straight path and merges into the central one at about 950 m depth.

The western tributary channel is 2 km wide with a sinusoidal path and NW-SE orientation and merges into the central structure at about 800 m depth.

Furthermore, in the adjacent southern sector of the studied area, the morphological survey has detected the presence of another channel, separated from the Marina di Gioiosa Canyon by the presence of a linear ridge that represents the western rim of the structure in exam.

The Marina di Gioiosa Canyon presents an average downslope along axis gradient of 53 m km^{-1} (longitudinal profile, see Figure 5), developed through a total length of about 12.7 km. The main features of the canyon rims, visualised in the transversal sections, are represented by slightly skewed sides, cutting the seafloor in a V-shaped valley in the upper part, about 900 m wide. Moving offshore, the canyon bottom flattens out and widens, the rims becoming more separated and less tilted and marked.

This latter conformation could be related to a more intense sediment input, that causes a greater erosion in association with the inlet of the two tributary channels at 800–950 m depth.

3.3. *Caulonia Marina Canyon*

The Canyon of Caulonia Marina is located in the North Eastern side of the surveyed area, in front of the mouths of three rivers: Allaro, Amusa and Precariti. These rivers and related hydrographic basins are less extended than the Torbido torrent, and are commonly named ‘Fiumare’ following their intermittent discharge regime.

The survey realised in this sector starts closer to the coastal zone, at less than 500 m from the shore limit, crossing the 20 m bathymetric contour and deepening to 70 m depth in correspondence with the canyon axis. In this case, the depth reached allows us to argue that the structure head is in real proximity to the shore limit.

The canyon appears like a single straight channel until 750 m depth, when the axis curves westward, in correspondence to an elevated ridge of the bottom that separates the two sides of the structure. In the shallower part, as in the Marina di Gioiosa Canyon, the canyon walls appear

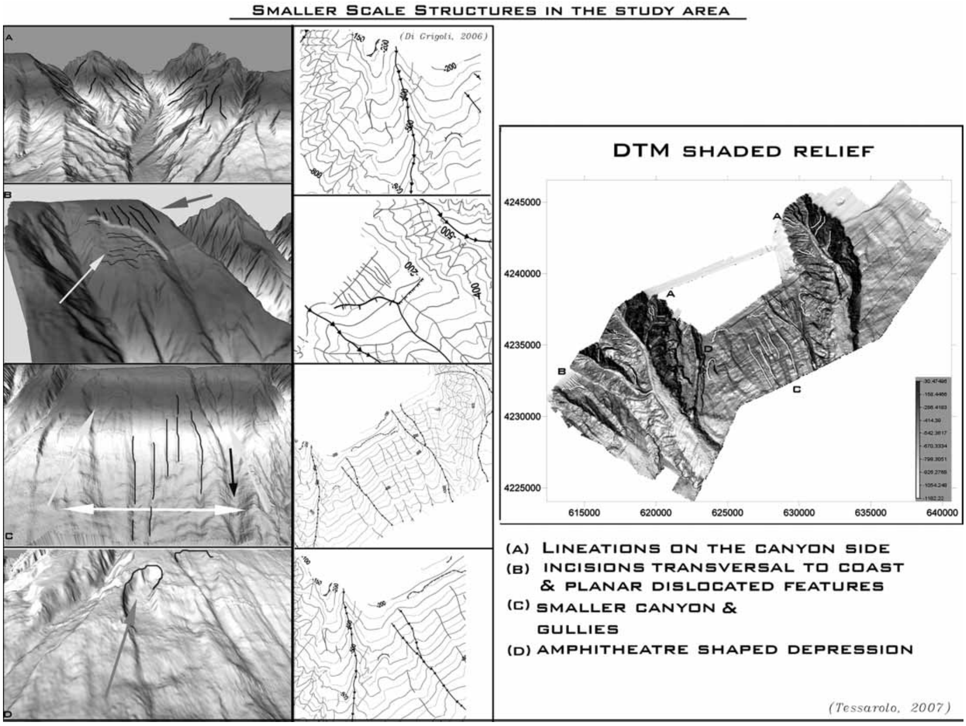

Figure 6. Smaller scale structures identified in the area. On the left side 3D sketches of the presented features are shown, associated to the geomorphological marine chart interpretation. On the right, the DTM planar view helps for structures location. (A) Incisions located on the Marina di Gioiosa eastern side. (B) Incisions transversal to the shore line in the upper part, while deeper are visible the terraces due to rotational slump. Behind them is visible the circular and steep headwall. (C) Gullies in the central part, surrounded by the deeper incision evaluated as a younger canyon. (D) Circular amphitheatre and scar related to slump phenomena.

strongly carved by sub-parallel, deep and straight grooves, more intense on the upper rims and on the western side.

The structure is about 2.5 km wide in the uppermost portion, close to the coastal zone, and 3.5 km wide at the survey limit offshore (>1150 m depth), with an average slope of 93 m km^{-1} (nearly twice the Marina di Gioiosa Canyon slope) developed along a 12.5 km length (longitudinal profile). The main morphological features of the canyon rims, visualised in the transversal sections (see Figure 5 for the realised profiles), are represented by a V-shaped morphology, with quite steep sides, related to an evolution dominated by erosional pattern. In the shallower portion, the central section shows an irregular positive structure in correspondence with the canyon thalweg, represented by ridges at different levels that modify the canyon bottom up to 910 m depth. In association to this structure, the canyon axis starts to rotate westward, its bottom becomes mostly flattened, and its rims develop a differentiated path: steep and shortened on the western side, gentle and more extended on the eastern side.

3.4. *Structures and morphologies associated with the two canyon systems*

In association with the main structures described above, interpretation of the MBES data set allowed us the recognition interpretation and mapping of features present on a smaller scale, which are important in evaluating and outlining the processes that acted in shaping the studied area (see Figure 6A, B, C, D for structural details).

In particular, the following structures were identified:

- *Lineations:* parallel grooves or striations with an uppermost linear path, traced downslope on the canyon rims and locally perpendicular to the shore limit in the south-western area. They could be related to the action of sediment transport processes from the main inland source or represent marks of local slides, both of them causing the scraping of side materials from the shelf to beyond-slope, following a preferential direction represented by the normal rim slope (gravitative processes). (See Figure 6A&B for location and detail).
  - Some grooves, limited to the shelf, transversal to the coastal line and with a minor length, are presumably due only to sediment mass transport delivered from the emerged sector, caused by intense meteorological events.
- *Planar structures with height difference:* on the eastern wall of the Marina di Gioiosa Canyon, planar structures at different levels cut a portion of the canyon upper side, probably generated by mass-wasting processes due to slumping or sliding of blocks. Their shape could probably be correlated to the rotation and subsequent removal of big block-masses (rotational slides). The terraces are graded following the downslope path, surrounded by a steep circular headwall, and this allows to hypothesise an influence of the normal slope deepening for their evolution (gravity influence), when the triggering event could be related to an intense mass (rock) slide (see Figure 6B for detail).
- *Gullies*: straight and parallel channels developed downslope and recognised at different depth along the sector of slope located between the two canyons. They could be related to the influence of sediments mass transport or generated by local failure episodes, correlated to the sediments derived from the coastal zone, presumably in concomitance of intense or extreme meteorological events (see Figure 6C).
- *Smaller Canyons:* quite close to the lateral limits of the major structures, the mass sediment transport has favoured the incision of two deeper channels, which probably represented the early stage of new canyon formation in the studied area. Differently from the Caulonia Marina and Marina di Gioiosa canyons, these small canyons seem to be restricted only to the slope, widening and slightly branched in the upper portion, without cutting the shelfbreak. This configuration could be related to a more recent formation of these structures, which cut the slope without yet reaching the limit of the shelfbreak, which seems to influence the ultimate morphology of the mature submarine canyon system [52] (Figure 6C).
- *Amphitheatre-shaped depressions:* these morphologies represent the headwall of slumps, identified by semi-circular scarps that signal the location of debris or rock removal (debris flow-slump; rock avalanche). Located in the upper and middle slope, they are presumably due to mass-wasting phenomena, triggered by intense sediment supply from the coastal zone, guided by the shape of the local slope (gravitative action). (See Figure 6D). Their presence also in correspondence of the canyons rims, with steep (up to vertical) bounding walls, allows us to hypothesise that they represent the location and cause of canyon widening, related to failure and mass delivery to deeper submarine environment (see Figure 6).

4. Discussion

Many erosive features have been detected along the investigated upper slope, generated by extensive mass wasting and canalised erosional flows that carry away sediments from coastal areas toward the basin. Canyons and other minor erosional linear features are common elements on the steep continental margin, with different characteristics that are function of geological context (lithology, structural setting, tectonic activity), oceanographic conditions and climate.

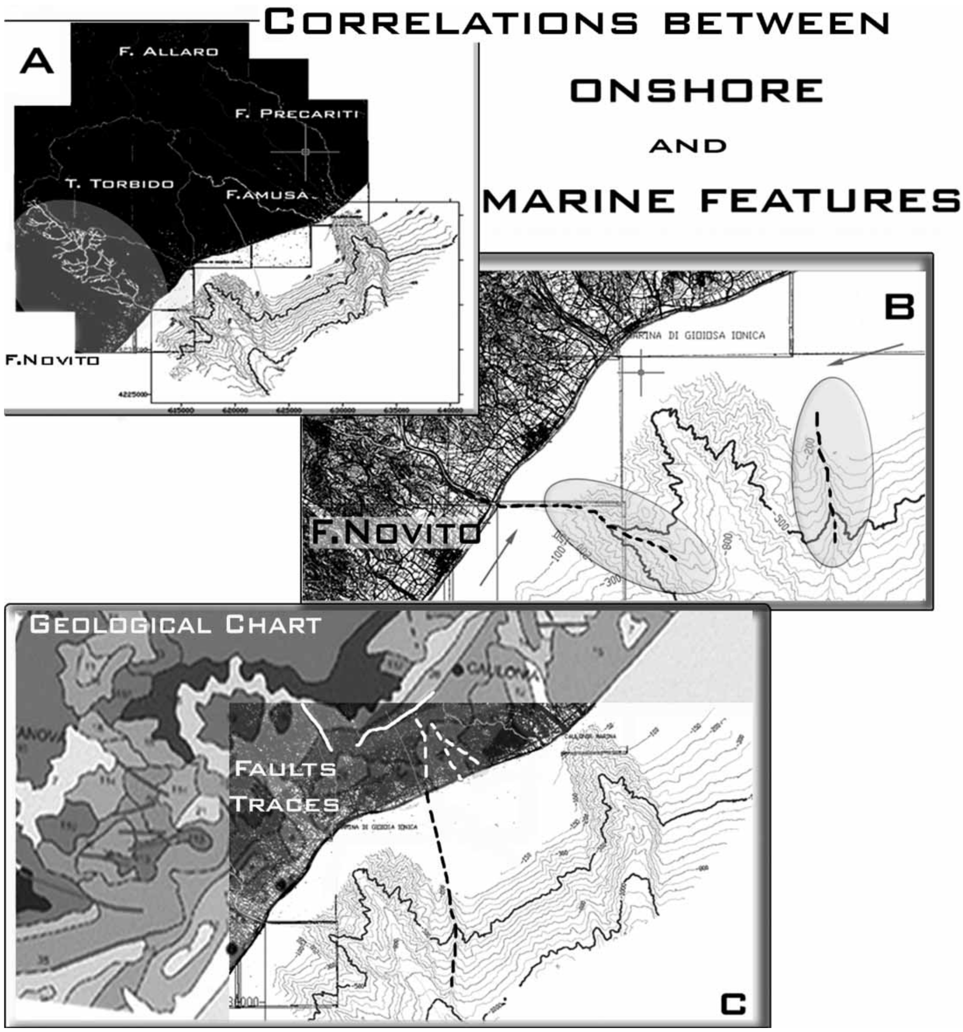

Figure 7. Structural correlation between the Marina di Gioiosa Canyon and features onshore: (A) General representation of the structures under examination, with the delineation of the Novito river hydrography. (B) Particular of the tributaries axis prolongation up to the coastal zone: on the left side, the connection with the Novito River is visible. (C) Correlation of the Geological Chart with the East tributary axis prolongation. The white lines indicate the fault trace onshore, that could presumably have determined a structural control on the Easter Marina di Gioiosa axis.

Although a comprehensive discussion of the several processes that are responsible of shaping for the erosional features described above would necessitate a more stratigraphic and structural data collection, thus is beyond the preliminary purpose of this paper. However, here we will discuss and speculate about the origin of these features on the basis of MBES imagery interpretation. As described above, the smallest features recognised in the area seem to have been primary linked and generated by the effects of gravitative phenomena, which are the cause of a large amount of sediments delivered from the inland source, favoured by the geo-structural and climatic background.

An interesting comparison concerns a two-scale feature detected: the canyons of Caulonia Marina and Marina di Gioiosa, and the deepest incisions located on the slope in the central studied sector.

The formation of the smallest structures seems to have been primarily related to a localised slump begin, here directed along the normal slope deepening, that in this location is emphasised by the structural background. Their extension, limited on the slope, could be related to an early growing phase for submarine canyon formation. The evolution of these phenomena, with scars growing headward, determines the reaching and breaching of the shelfbreak [52]. After this situation, new erosion mechanisms could occur: the sediments delivered from the coastal zone are mostly channelled in the incisions created, conveying the shelf materials on the slope and more over, scraping and widening the uppermost part of the focussed lineation. This configuration is typical for features in a mature phase [52] which have been affected by intense and prolonged retrograded phenomena.

The major structures, represented by the Caulonia Marina and Marina di Gioiosa canyons, even if they could both be interpreted as mature canyons, present some difference in their structural conformation.

The Marina di Gioiosa canyon head appears more wide and articulated, with the hypothesised upper limit located very close to the shore line. The presence of tributaries and the less marked inclination evaluated, in association to a near flattened base offshore, allow to hypothesise a longer impact of mass sediment, transported through the structure. This path was probably major on the central channel, as demonstrated by his flattered axis shape and by the hanging (less incised) nature of the lateral tributaries. In this situation probably the mechanism of removal of foot material causes the progressive instability of the canyon walls, shaping the development of ‘retrogradational’ slides that destabilise the uppermost walls portion, moving upward, as a consequence of subsequent events. The slide mass deposits built at the base of the walls are periodically removed by erosional fluxes that run along the canyon thalweg, shaping and deepening the main channel and improving the gravitational walls instability.

On the other hand, in the Caulonia Marina Canyon the presence of the central ridge could be presumably related to a not well organised mass transport, that generates structures similar to ‘like river braided system’ meanders at the canyon bottom, and where the ridge constitutes the mark left by such articulated erosion pattern.

These geomorphic considerations allow the hypothesis that the Marina di Gioiosa Canyon could represent the oldest and more mature structure detected in the studied area.

The Caulonia Marina canyon is also in a mature stage, for the shelf scraping close to the shore line, but the sediment excavation has been presumably minor; this could be caused either by a more recent formation, or by a less important mass transport input, derived from the smaller onshore rivers.

The evolution of the two major canyon systems, differing by minor structures, could have been influenced by their connection to the ‘Fiumare’ outfalls. Actually, during the Pleistocene glacio-eustatic lowstands the heads of Marina di Gioiosa Canyon and Caulonia Marina Canyon could have presumably caught sediment supply from the coastal drift. Then the sediments drifted downward the canyon systems, especially during floods, violent sea storms or telluric shocks, forming tourbiditic currents that scoured and deepened the thalweg. A detailed characterisation and definition of the direct link between on land structures and the development of these canyons will however be possible only after the completion of the geophysical survey in the bathymetric portion close to the coastline, not yet realised within this preliminary work.

On the other hand, in regard to a few features, indication of structural control can be pointed out, for instance the eastern lateral tributary merging to Marina di Gioiosa Canyon at about 950 m of depth. The linearity of its trend has led to the hypothesis of a structural fault control, oriented in a NE–SW direction: this is also supported by the relationship with the existing cartography for the emerged area [53], where structural lineations have been recognised in the coastal zone close behind the evaluated elements (see Figure 7 for this assumption). Also Cuppari et al. [54], in their integrated seismic-acoustic study of Ionian Calabrian inner margin, supported the influence of tectonic lineaments in generating slope erosional structures on the slope.

5. Conclusions

The survey performed in the coastal zone located between Marina di Gioiosa and Caulonia Marina has allowed us to trace a preliminary evaluation of the morphological features of the selected area. This zone is currently characterised by a steep margin, affected by high relief close to the coastal zone, and by a narrow extension of the shelf, both related to the interaction between a strong and still active neo-tectonic activity, started in the Miocene for the migration and uplift of the Calabrian Arc, and the eustatic sea level oscillations of the Quaternary. This uplift path of the emerged area, coupled to the typical climatic regimes, determines a large intermittent amount of sediments, that more than in other places impacts on the shelf structures and emphasises the transport-erosion pattern with respect to the depositional one. This evolution determined the development of the erosional features recognised in the area, which show very variable morphological characteristics that could be presumably due to a different degree of growing. Both erosive bottom-up and top-down processes have been detected along the upper slope, related to retrogressive slope failures [52,55,56] and down-slope eroding sediment flows [55] respectively. It is possible that both mechanisms have cooperated in generating the major elements imaged by the acoustical data collected that are represented by the two canyon systems, named Caulonia Marina and Marina di Gioiosa. The shallow depth crossed by these structures in the coastal zone has pointed out how their origin must be very close to the shore limit, a situation that is commonly defined for features in a mature phase [52]. Deep incisions present on the slope could represent the youthful evolution phase of submarine canyons, where the headward scraping by sediments delivered from the inland input has not breached instead the shelf-break limit.

In relation to minor features, like incisions, grooves and gullies, their linearity and downslope path allows to relate them primarily to the influence of gravitative erosional mass transport. This could also be the triggering factor for the development of graded terraces, linked to the rotational slump of blocks, and of the amphitheatre shaped depressions, related to debris or block mobilisation and avalanches. For these assumptions, it is evident that the working area has been, and currently is, subjected to intense mass transport and removal events. These are coupled to a strong influence in their delivery by a gravitative component, linked primary to the geological background of the uplifted active margin, and enhanced by the climatic regime, that causes very intense and seasonal, sometimes catastrophic, meteorological events. The features generated by gravitative phenomena are also presumably related to the seismicity that characterises the Calabrian region, due to the still active tectonic control. Finally, the relation between the observed structures and the morphologies on the emerged coastal sector has outlined new interesting perspectives: the Novito river, located South West of the survey area, seems to be located in correspondence to the prolongation of the western tributary channel merging to the Marina di Gioiosa Canyon, and is likely to play a role in the development of the submerged structure. On the basis of this assumption, the Novito river, not considered in the original project plan, has been added to the torrents selected for the study purpose, particularly as a possible influence factor for the Marina di Gioiosa Canyon formation and evolution, in association with the Torbido river.

References

[1] P.A. Pirazzoli et al., *Late Holocene emergence in Calabria, Italy*, Mar. Geol. 141 (1997), pp. 61–70.
[2] K. Lambeck et al., *Sea-level change along the Italian coast for the past 10,000 yr*, Quat. Sci. Rev. 23 (2004), pp. 1567–1598.

[3] B. Dumas, P. Guérémy and J. Raffy, *Evidences for the sea-level oscillation by the "characteristic thickness" of marine deposits from raised terraces of Southern Calabria (Italy)*, Quat. Sci. Rev. 24 (2005), pp. 2120–2136.
[4] H. Ibbeken and R. Schleyer, *Source and Sediment. A Case Study of Provenence and Mass Balance at an Active Plate Margin (Calabria, Southern Italy)*. Springer, Berlin, 1991, 286pp.
[5] L. Sabato and M. Tropeano, *Fiumara: A kind of high hazard river*, Phys. Chem. Earth 29 (2004), pp. 707–715.
[6] F. Antonioli et al., *Elevation of the last interglacial highstand in Sicily (Italy): A beachmark of coastal tectonics*, Quat. Int. 145–146 (2006), pp. 3–18.
[7] A. Malinverno and W.B.F. Ryan, *Extension in the Tyrrhenian Sea and shortening in the Appennines as a result of arc migration driven by sinking of the lithosphere*, Tectonics 5 (1986), pp. 227–245.
[8] R. Catalano et al., *On the Mesozoic Ionian Basin*, Geophys. J. Int. 144 (2001), pp. 49–64.
[9] J. F. Dewey, M.L. Helman, E. Turco, D.W.H. Hutton, and S.D. Knott, *Kinematics of the Western Mediterranean*, in *Alpine Tectonics,* M.P. Coward, D. Dietrich and G. Park, eds, Geological Society London Special Publication, 1989, 45, pp. 265–283.
[10] J. Dercourt, L. E. Ricou, and B. Vrielynk, eds, *Atlas Tethys Paleoenvironmental Maps*, 14 maps, 1 plate, Gauthier-Villars, Paris, 1993, 307pp.
[11] W. Cavazza et al., *Stratigrafia e sedimentologia della sequenza sedimentaria oligocenico-quaternariadel bacino calabro-ionico*, Boll. Soc. Geol. Ital. 116 (1997), pp. 223–241.
[12] W. Cavazza and P. DeCelles, *Upper Messinian siliciclastic rocks in southeastern Calabria (Southern Italy): Palaeotectonic and eustatic implications for the evolution of the central Mediterranean region*, Tectonophysics 298 (1998), pp. 51–77.
[13] B. Dumas, P. Guérémy, R. Lhénaff, and J. Raffy, *Découverte à 157 m d'altitude, près de Nocella (Italie di Sud) du plus haut rivage tyrrhénien connu à ce jour*, Comptes Rend. Acad. Sci. Série II 305 (1987), pp. 139–142.
[14] R. Westaway, *Quaternary uplift of southern Italy*, J. Geophys. Res. B 98 (1993), pp. 21741–21772.
[15] L. Tortonici , C. Monaco, C. Tansi, and O. Cocina, *Recent and active tectonics in the Calabrian arc (Southern Italy)*, Tectonophysics 243 (1995), pp. 37–55.
[16] C. Monaco, L. Tortonici, R. Nicolich, L. Cernobori, and M. Costa, *From collisional to rifted basin: An example from the southern Calabria arc (Italy)*, Tectonophysics 266 (1996), pp. 233–249.
[17] D.F. Williams, R.C. Thunnel, E. Tappa, D. Rio, and I. Raffi, *Chronology of the Pleistocene oxigen isotope record, 0 – 1,88 M.yr B. P.,* Paleogeog. Paleoclim. Paleoecol. 61 (1988), pp. 221–240.
[18] B. Dumas, P. Guérémy, R. Lhénaff, and J. Raffy, *Terrasses quaternaires soulevées sur la façade calabraise du Détroit de Messine (Italie)*, Comptes Rend. Acad. Sci. D 90 (1980), pp. 739–742.
[19] T. Miyauchi et al., *Geochronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of south Calabria, Italy*, Quaternario 7 (1994), pp. 17–34.
[20] G. Dai Pra et al., *Età dei depositi a Strombus Bubonius di Vibo Valentia Marina (Italia Meridionale)*, Quaternario 6 (1993), pp. 139–144.
[21] F. Antonioli and G. Leoni, *Technical report ENEA for the Environmental Ministry, Project 4.8(3b)*, 2000, 45pp.
[22] F. Antonioli et al., *The risk of sea flooding in 33 Italian coastal plain. Workshop global climate changes during the late Quaternary*, Accademia dei Lincei of Rome, Abstract volume, 2001, pp. 29–43.
[23] C. Monaco et al., *The geological map of the urban area of Catania (Sicily): Morphotectonic and seismotectonic implications*, Mem. Soc. Geol. Ital. 5 (2001), pp. 425–438.
[24] F. Antonioli et al., *Holocene sea-level change in Sicily, and its implications for tectonic model: new data from the Taormina area, NE Sicily*, Mar. Geol. 196 (2003), pp. 53–71.
[25] K. Lambeck and P. Johnston, *Land subsidence and sea-level change: Contributions from the melting of the last great ice sheets and the isostatic adjustment of the Earth*, in *Land Subsidence*, F.J. Barrends, F.J.J. Brower and F.H. Schröeder, eds, The Hague, 16–20 October 1995. Balkema, Rotterdam, 1995, pp. 3–18.
[26] N.J. Shackleton, *The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide and orbital eccentricity*, Science 289 (2000), pp. 1897–1902.
[27] D.W. Lea et al., *Reconstructing a 350 ky history of sea level using planktonic Mg/Ca and oxygen isotope records of Cocos Ridge core*, Quat. Sci. Rev. 21 (2002), pp. 283–293.
[28] C. Waelbroeck et al., *Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records*, Quat. Sci. Rev. 21 (2002), pp. 293–305.
[29] J. Jouzel et al., *Atmospheric oxygen 18 and sea level changes*, Quat. Sci. Rev. 21 (2002), pp. 307–314.
[30] T.M. Esat et al., *Rapid fluctuations in sea level recorded at Huon Peninsula during the penultimate deglaciation*, Science 283 (1999), pp. 197–201.
[31] K. Lambeck, *Glacial links between climate and sea level for the past three million years*, Nature 419 (2002), pp. 199–206.
[32] G. Shellmann and U. Radtke, *The coral reef terraces of Barbados: A guide*, International Conference on 'Quaternary Sea-Level Change', Barbados, 26 Oct–2 Nov 2002, 118pp.
[33] G. Shellmann and U. Radtke, *A revised morpho- and cronostratigraphy of the late and m middle Pleistocene coral reef terraces on Southern Barbados (West Indies)*, Earth Sci. Rev. 64 (2004), pp. 157–187.
[34] E.K. Potter and K. Lambeck, *Reconciliation of sea-level observations in the Western North Atlentic during the last glacial cycle*, Earth Planet. Sci. Lett. 217 (2003), pp. 171–181.
[35] E.K. Potter et al., *Suborbital-period sea-level oscillations during marine isotope substages 5a and 5c*, Earth Planet. Sci. Lett. 225 (2004), pp. 191–204.
[36] K.B. Cutler et al., *Rapid sealevel fall and deep-ocean temperature change since the last interglacial period*, Earth Planet. Sci. Lett. 206 (2003), pp. 253–271.

[37] C.H. Stirling et al., *Timing and duration of the Last Interglacial: evidence for a restricted interval of a widespread coral reef growth*, Earth Planet. Sci. Lett. 160 (1998), pp. 745–762.
[38] P.J. Hearty, *An inventory of the last interglacial (s.l) age deposits from the Mediterranean basin: a study of isoleucine epimerization and U-series dating*, Zeitschr. Geomorph. Supplement Band, 62 (1986), pp. 51–59.
[39] C.L. Hillaire-Mercel et al., *Th/U dating of* Strombus bubonius *bearing marine terraces in southern Spain*, Geology 14 (1986), pp. 613–616.
[40] C.L. Hillaire-Mercel et al., *U-Series measurements in Tyrrhenian deposits from Mellorca: Further evidence for two last-interglacial high sea levels in Balearic Islands*, Quat. Sci. Rev. 15 (1996), pp. 53–62.
[41] P.J Hearthy and G. Dai Pra, *The age and stratigraphy of quaternary coastal deposits along the Gulf of Taranto (South Italy)*, J. Coastal Res. 11 (1992), pp. 675–689.
[42] P. Kindler et al., *Tyrrhenian coastal deposits from Sardinia (Italy): A petrographic record of high sea levels and shifting climate belt during the last interglacial (isotopique stage 5e)*, Palaeogeog. Palaeoclim. Palaeoecol. 133 (1997), pp. 1–25.
[43] C. Zazo *Interglacial sea level*, Quat. Int. 55 (1999), pp. 101–113.
[44] Y. Jedoui et al., *Analise sédimentologique des depots marins pléistocenès du Sud-Est tunisien: mise en evidence de deux pérodies de haut niveau marin pendant le sous-state isotopique marine 5e (Eémien, tyrrhènien)*, Bull. Soc. Gèol. France 173 (2002), pp. 63–72.
[45] Y. Jedoui et al., *U-series evidence for two high Last Interglacial sea levels in southeastern Tunisia*, Quat. Sci. Rev. 22 (2003), pp. 343–351.
[46] M. Zecchin, R. Nalin, and C. Roda, *Raised Pleistocene marine terraces of the Crotone peninsula (Calabria, southern Italy): Facies analysis and organization of their deposits*, Sed. Geol. 172 (2004), pp. 165–185.
[47] W. R. Peltier, *Mantle viscosity and ice-age ice sheet topography*, Scienze 273 (1996), pp. 1359–1364.
[48] S. Rossi and R. Sartori, *A seismic reflection study of the External Calabrian Arc in the Northern Ionian Sea (Eastern Mediterranean)*, Mar. Geophys. Res. 4 (1981), pp. 403–426.
[49] L. Cernobori et al., *Crustal image of the Ionian basin and its Calabrian margins*, Tectonophysics 264 (1996), pp. 175–189.
[50] E.Morlotti, R.Sartori, L.Torelli, F. Barbieri, and I. Raffi, *Chaotic deposits from the External Calabrian Arc (Ionian Sea, Eastern Mediterranean)*, Mem. Soc. Geol. Ital. 24 (1982), pp. 261–275.
[51] CNR, Structural Model of Italy, Sheet N. 6, S.EL.CA., Florence, Italy, 1991.
[52] J. A. Farre, B.A. McGregor, W.B.F. Ryan, and J.M. Robb, *Breaching the shelfbreak: Passage from youthful to mature phase in submarine canyon evolution*, in *The Shelfbreak: Critical Interface on Continental Margins,* J. D. Stanley and G. T. Moore, eds, Special Publication No.33, Society of Economic and Paleontologist and Mineralogists, 1983, pp. 25–33.
[53] VV. AA. Calabrian Geological Map, Scale 1:250 000. Corinne Land Cover Project, modified from: *Carta Geologica D'Italia*' [Scale 1:500,000] and '*Carta delle Grandi Frane e Deformazioni Gravitative Profonde di Versante della Calabria*' [Scale 1:250,000], CNR/I.R.P.I. (CS). Available online at: http://88.41.139.89/cartografia/spazio/carta_geologica.asp
[54] A. Cuppari, F. Fanucci, D. Morelli, E. Colizza, D. Lenaz, D. Accettella, and W. Nigel, *Morphostructural features and sedimentary processes of the Ionian Calabrian Inner Margin.* Workshop GEOITALIA 2007, Rimini, Epitome, 2007, 2, 864 pp.
[55] D.C. Twichell and G. Roberts David, *Morphology, distribution, and development of submarine canyons on the United States Atlantic continental slope between Hudson and Baltimore Canyons*, Geology 10 (1982), pp. 408–412.
[56] R.A. Daly, *Origin of submarine "canyons"*, Am. J. Sci. Ser. 5, 31 (1936), pp. 401–420.

Appendix 1: Geophysical Data Acquisition

The geophysical data have been acquired using the 8160 Seabat MultiBeam Echosounder that with its 50 kHz frequency is generally used to detect intermediate depth (from 50 m to 2500 m for the best acquisition).

This instrument uses principles of acoustic waves reflection to calculate the depth value, converting in distance the time span between signal emission from the transducer and its return (it is defined a form of 'remote sensing').

Differently from Single Beam Echosounders, the Multibeam generates 126 simultaneous high-resolution receive beams, that produce a swath of 150° degree amplitude to detect the water depth.

The preliminary phase of data acquisition interested the calibration of the signal received, realised to compensate the Roll, Pitch and Heave movements.

During acquisition, the system received positioning parameters from a Differential Global Positioning System (DGPS), while the right evaluation of the depth values was improved by the acoustic waves velocity propagation profile, derived from the Sound Velocity Profiler (SVP) realised daily during the survey.

Geodetic Parameters:

System: WGS 84
Projection:Universal Transverse Mercatore (UTM)
Zone: 33
Lat. Orig.: 0°00'00" - Long. Orig.: 15°00'00"
False Easting: 500000 – Scale Factor: 0.9996.

SEABAT 8160 Parameters:
Frequency: 50 kHz
Depth resolution: 1.4/2.9/8.6 cm (range dependent)
Swath coverage: Greater than 4× water depth
Max operational depth: 3000 m
Number of beams: 126
Along-Track beamwidth: 1.5°, 3.0°, 4.5°, 6.0° (selectable)
Across-Track beamwidth: 1.5° at nadir
Pitch stabilisation: ±10°
Accuracy: IHO Special Order
Operational speed: Up to 20 knots
Max. update rate: 15
Transducer depth rating: 100 m

Appendix 2: Data Processing

Processing of the geophysical data consisted of the following steps:

- the spike errors have been removed manually from the survey lines collected;
- the data have been plotted in a grid having a cell size of 10 and 20 m. The best representation has been obtained for the 20 m cell size, as presumed for the depth of the deeper sector;
- the grid have been interpolated with different statistical methods, to fill some acquisition gaps;
- finally, it has been exported to realise the contour chart and the Digital Terrain Model (DTM).