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Megafauna of vulnerable marine ecosystems in French mediterranean submarine canyons: Spatial distribution and anthropogenic impacts

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Abstract:

Vulnerable Marine Ecosystems (VME) in the deep Mediterranean Sea have been identified by the General Fisheries Commission for the Mediterranean as consisting of communities of Scleractinia (*Lophelia pertusa* and *Madrepora oculata)*, Pennatulacea (*Funiculina quadrangularis)* and Alcyonacea (*Isidella elongata*). This paper deals with video data recorded in the heads of French Mediterranean canyons. Quantitative observations were extracted from 101 video films recorded during the MEDSEACAN cruise in 2009 (Aamp/Comex). Qualitative information was extracted from four other cruises (two Marum/Comex cruises in 2009 and 2011 and two Ifremer cruises in 1995 and 2010) to support the previous observations in the Cassidaigne and Lacaze-Duthiers canyons. All the species, fishing impacts and litter recognized in the video films recorded from 180 to 700 m depth were mapped using GIS. The abundances and distributions of benthic fishing resources (marketable fishes, Aristeidae, Octopodidae), Vulnerable Marine Species, trawling scars and litter of 17 canyons were calculated and compared, as was the open slope between the Stoechades and Toulon canyons. *Funiculina quadrangularis* was rarely observed, being confined for the most part to the Marti canyon and, *I. elongata* was abundant in three canyons (Bourcart, Marti, Petit-Rhône). These two cnidarians were encountered in relatively low abundances, and it may be that they have been swept away by repeated trawling. The Lacaze-Duthiers and Cassidaigne canyons comprised the highest densities and largest colony sizes of scleractinian cold-water corals, whose distribution was mapped in detail. These colonies were often seen to be entangled in fishing lines. The alcyonacean *Callogorgia verticillata* was observed to be highly abundant in the Bourcart canyon and less abundant in several other canyons. This alcyonacean was also severely affected by bottom fishing gears and is proposed as a Vulnerable Marine Species. Our studies on anthropogenic impacts show that seafloor disturbance by benthic fishing is mainly attributable to trawling in the Gulf of Lion and to long lines where rocky substrates are present. The bauxite residue (red mud) expelled in the Cassidaigne canyon was seen to prevent fauna from settling at the bottom of the canyon and it covered much of the flanks. Litter was present in all of the canyons and especially in considerable quantities in the Ligurian Sea, where the heads of the canyons are closer to the coast. Three Marine Protected Areas and one fishing area with restricted access have recently been established and should permit the preservation of these deep ecosystems.

Keywords : Seafloor mapping ; Biodiversity ; Bathyal-benthic zone ; Cold-water coral ; Litter ; Fishing impact ; Bauxite red mud waste ; Mediterranean Sea ; French submarine canyons (43°N, 5°E)

1. Introduction

There has been increasing societal demand for the conservation of biodiversity since the Convention on Biological Diversity recognised the intrinsic value of biological diversity and its ecological, genetic, social, economic, scientific, educational, cultural and recreational benefits at the 1992 Earth Summit in Rio de Janeiro (http://www.cbd.int/). Considerable efforts have been made in recent years through the ten-year Census of Marine Life Project to estimate biodiversity in the oceans (Costello et al., 2010). Nevertheless the total number of marine species is still unknown because many species remain to be sampled, distinguished and described (Bouchet, 2006). Less is known about deep-sea areas compared to coastal environments due to the practical difficulties of sampling deeper waters. However, there is a pronounced shift of fisheries from shallow to much deeper regions, motivated by the declining fish stocks on the continental shelves (Cartes et al., 2004) and by the advanced fishing gear technology now available for the efficient exploitation of the bathyal zone. Despite this, deep-water ecosystems are characterized by low productivity, low fecundity, older age at first maturity and high longevity of the species adapted to these environments; thus they are highly sensitive to commercial exploitation.

Adverse impacts to Vulnerable Marine Ecosystems (VME) in the deep sea have now become an international concern since the United Nations called on governments and Regional Fishery Management Organisations to prevent them (United Nation, 2007). The Food and Agriculture Organisation (FAO) has formulated management guidelines, by setting up an international consultative process and determining criteria for defining VMEs (FAO, 2009). The latter include uniqueness or rarity of species or habitat, their functional significance, fragility and structural complexity, and life histories that limit the probability of recovery. Examples of taxa indicative of a VME are given associated with specific undersea landscape types, but no explicit metrics, threshold values, or analytical approaches are given for identifying whether one area contains a VME and another does not (Auster et al., 2011). The biggest constraints in protecting VMEs are the uncertainties in the distribution and abundance of VME indicator species, and similar uncertainties in the link between fishing intensity and significant adverse impacts. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR for Oslo-Paris) has worked to identify the threats to the marine environment and has pioneered the development of methods for monitoring and assessing the quality status of seas. The OSPAR Commission has established a list of threatened and/or declining species and habitats in the OSPAR maritime area that require protection. The deep-sea habitats mentioned in the OSPAR list are coral gardens, *Lophelia pertusa* reefs, deep-sea sponge aggregation and sea-pen and burrowing megafauna communities (http://www.ospar.org).

Compared to the adjacent deep Atlantic basins the Mediterranean Sea is a warm, deep, oligotrophic basin where temperatures remain largely uniform but at much higher levels, i.e. around 12.5-14.5°C below 150 m, with high salinity (38.4-39.0) and high oxygen levels (4.5-5.0 ml. l^{-1}) (Cartes et al., 2004). The western Mediterranean basin is connected to the Atlantic by the narrow Strait of Gibraltar, with a sill depth of about 300 m, and to the eastern Mediterranean basin by the Sicily Channel (400 m). These gateways funnel the entire exchange of water mass between the eastern and western basin (Sicily Channel) and with the Atlantic Ocean (Strait of Gibraltar), thereby following the pattern of anti-estuarine circulation (Astraldi et al., 1999). These features distinguish Mediterranean deep-sea communities as being potentially unique and particularly sensitive to human activities. The continental shelves are narrow, except close to the outlets of major rivers (the Rhône in the western basin) (Cartes et al., 2004) and are incised by numerous submarine canyons. Much of the Mediterranean coast has deep-water bottoms near the shore, typically reached within a few hours by commercial vessels. The Mediterranean stands out as a globally different region because its canyons are more closely spaced (14.9 km), more dendritic (12.9 limbs per 100,000 km^2), shorter (mean length of 26.5 km) and steeper (mean slope of 6.5°) than canyons found in other regions of the world (Harris and Whiteway, 2011).

The General Fisheries Commission for the Mediterranean (GFCM) has issued a list of criteria for the identification of sensitive habitats of relevance for the management of priority species in the Mediterranean Sea (GFCM, 2009a). The GFCM has also issued a list of identified sensitive habitats including: (1) cold-water corals (*Lophelia pertusa* and *Madrepora oculata* communities) which form colonies supported by a common skeleton, providing a structural habitat for other species (Peres and Picard, 1964; Zibrowius, 1980); (2) soft mud facies with *Funiculina quadrangularis* (Bellan-Santini et al., 2002; Peres and Picard, 1964), which is an essential habitat for certain crustacean species (*Parapenaeus longirostris* and *Nephrops norvegicus*); and (3) compact mud facies with *Isidella elongata* (Bellan-Santini et al., 2002; Maurin, 1962; Peres and Picard, 1964), which is a relevant habitat for red shrimps (*Aristeus antennatus* and *Aristaeomorpha foliacea).* These habitats are potentially vulnerable as they are targeted by fisheries. Another anthropogenic pressure affecting seafloor integrity includes silting which can change the environmental conditions of the habitats. For instance the Cassidaigne canyon, near Marseille, France, has received red mud discharged by the Gardanne Aluminium factory since 1967. Red mud extends into the abyssal plain more than 50 km away from the pipe (Dauvin, 2010; Fontanier et al., 2012).

All the pressures on natural marine resources and the demand for marine ecological services are considered excessive and have led to the establishment of the European Marine Strategy Framework Directive (MSFD). This marine environmental policy established in 2008 aims at reducing impacts on marine waters, by considering that the marine environment is a precious heritage that must be protected, preserved and, where practicable, restored, with the ultimate aim of maintaining biodiversity and providing diverse and dynamic oceans and seas which are clean, healthy and productive. The final objective of the MSFD is to achieve or maintain good environmental status in the marine environment by 2020 at the latest. The work described in this paper was performed in the framework of the initial assessment of the bathyal benthic ecosystems in the French submarine canyons of the Mediterranean Sea.

We used a Geographic Information System (GIS) to map all the species and ecosystems recognized on video films recorded during the MEDSEACAN cruise in 2009 (Watremez, 2012), the MARUM cruise in 2009, the MARUM-Senckenberg cruise in 2011, the Ifremer ESSROV cruise in 2010 and the CYATOX cruise in 1995. We assessed their spatial distribution from 180 m to 700 m depth in the heads of French canyons. Three objectives were pursued: (1) mapping benthic fishing resources; (2) mapping Vulnerable Marine Ecosystems recognised by the General Fisheries Commission for the Mediterranean (GFCM, 2009a); and (3) assessing the distribution and threat of anthropogenic impacts on benthic ecosystems including fishing activities and waste disposal.

2. Materials and methods

2.1 Study area

The study area covers the shelf break and the bathyal zone of the French continental margin of the northwest Mediterranean Sea, stretching from 42°30'N to 43°30'N and from 3 to 7°E. This continental slope is divided into two regions, namely the Gulf of Lion and the French Riviera (Ligurian Sea). The Gulf of Lion has a broad shelf (wider than 100 km) with a gentle slope, stretching from the coast to the shelf break. The continental shelf off the French Riviera is narrow (2-20 km wide) with a steep slope. The French continental slope is dissected by several canyons in the Mediterranean Sea (from 180 to 2000 m). Seventeen were taken into account in this study, as was the open slope between the Toulon and Stoechades canyons (Fig. 1).

Water circulation is generally westward along the continental slope and is constrained by two dominant winds: north-northwesterly winds (upwelling favourable winds) and southeasterly winds (downwelling favourable winds). Prevailing winds from north-west to west (Mistral) cause the displacement of warm surface waters to the open sea, generating six upwelling locations in the Gulf of Lion (Millot, 1990). In combination with the morphology of the coast-line, the Mistral leads to the most intense upwelling of the Gulf of Lion, which rises from the Cassidaigne canyon off Marseille (Alberola and Millot, 2003). During winter, both heat loss and evaporation lead to the cooling and mixing of the coastal waters in the Gulf of Lion. These cold shallow waters finally become denser than the surrounding waters and sink, forming currents known as dense shelf water cascades (DSWC). They carry huge amounts of sediment and organic matter to the deep ocean as they scour the shelf and seafloor slope while sinking. The source area of DSWC is located off Perpignan in the Gulf of Lion (Canals et al., 2006; Durrieu de Madron et al., 2005).

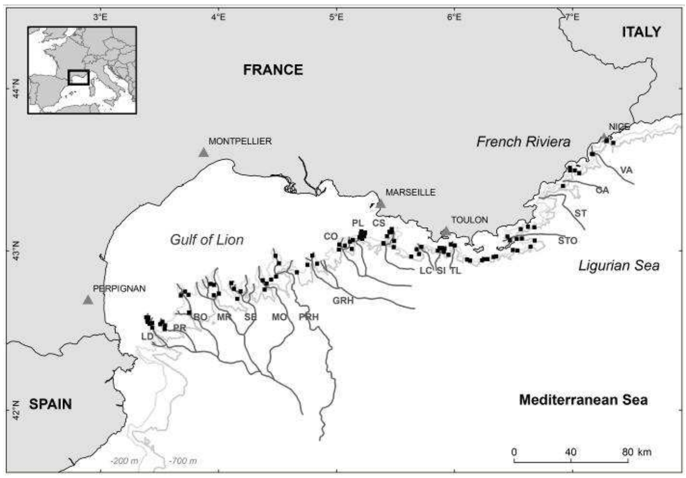

Fig. 1. *The French continental margin of the Mediterranean Sea dissected by a series of submarine canyons.*
From West to East: LD: Lacaze-Duthiers, PR: Pruvost, BO: Bourcart (Aude), MR: Marti (Hérault), SE: Sète, MO: Montpellier, PRH: Petit Rhône, GRH: Grand Rhône, CO: Couronne, PL: Planier, CS: Cassidaigne, LC: La Ciotat, SI: Sicié, TL: Toulon, STO: Stoechades, ST: Saint-Tropez (not considered in this study), CA: Cannes, VA: Var. Black squares represent the dives considered in this study (> 180 m depth) during the MEDSEACAN 2009, MARUM 2009, MARUM-Senckenberg 2011, ESSROV 2010 and CYATOX 1995 cruises.

2.2 Data origin

2.2.1 New data

Recent data were collected during the MEDSEACAN cruise organised by the “Agence des aires marines protégées” (Aamp) in 2009. The aim of the cruise was to explore the head of the canyons and so it was not specifically dedicated to the census of Vulnerable Marine Species. The data obtained from a total of 101 dives performed with the 'Super Achille' Remotely Operated Vehicle (ROV) from Comex (www.comex.com) are used for this paper (Table 1). The manned submersible ‘Remora’ was also deployed during the MEDSEACAN cruise, but the video films taken were not processed for this study, apart from one taken during a dive in the Bourcart canyon (BO_R2K_P1). Seventeen submarine canyons dissecting the French continental slope in the Mediterranean Sea, and the open slope between the Toulon and Stoechades canyons were explored in the bathyal bathymetric zone, from 180 to 700 meters depth (Fig. 1).

Additional video films were collected during two other cruises with the Comex team: the 2009 MARUM cruise (R/V "Minibex"; P.I. D. Hebbeln) to the Cassidaigne canyon and the 2011 MARUM-Senckenberg cruise (R/V "Minibex"; P.I. S. Tesche) to the Lacaze-Duthiers canyon (Table 2). The 'Super Achille' ROV and the manned submersible 'Remora' were deployed to collect colour video films and digital images and, exceptionally, a few samples. Data from four more dives were processed qualitatively: one dive with the Ifremer manned submersible Cyana (dive 1214-03 during the cruise CYATOX in 1995 (R/V "Le Suroit"; P.I. F. Galgani) and three dives (397-01, 401-05, 407-11) with the Ifremer Victor 6000 ROV from cruise ESSROV in 2010 (R/V "Pourquoi Pas?"; P.I. P. Simeoni) (Table 2). The global bathymetric map (100 m grid) of the French Mediterranean coast was compiled at Ifremer from different cruises (Loubrieu and Satra, 2010). The detailed bathymetric map (10 m grid) of the Bourcart canyon was obtained from the Marion 2000 cruise (Berné, 2000).

2.2.2 Historical data

Distribution maps of several Vulnerable Marine Ecosystems were digitalized from old documents in order to complete the information gathered from submersible exploration. The distribution of *Isidella elongata* and *Funiculina quadrangularis* were assessed previously in the Gulf of Lion and in the Ligurian Sea by trawling (Carpine, 1964; Fredj, 1964; Maurin, 1962).

2.3 Processing of video and navigation data

The exploratory dives were performed by the ROV equipped with two cameras. One was fixed to a pan and tilt mount used by the pilots and recorded continuously on DVcam tapes and a hard disk recorder. The other was fixed and mounted under the first one. This camera was equipped with a zoom and could record HD images and HD video, but not continuously. The ROV navigation data were derived from the SSBL subsea positioning system, Kongsberg HPR 410, and the surface positioning system, DGPS AG132 – Trimble and Vector – Hemisphere GPS.

The distribution of communities, species and other objects and features (e.g. litter and fishing impacts) was mapped along dive tracks from video studies of each dive, using the Ifremer underwater vehicle data post-processing software "Adelie" (www.ifremer.fr/adelie) including an extension for the ArcGIS 9.3 software suite (© ESRI). The navigation files included date, time, latitude, longitude, heading and depth. All the Super Achille navigation track data had to be formatted manually in order to enter the dedicated Ifremer "Adelie" extension. The navigation data were post-processed using Gaussian smoothing. For the sake of practicality, the video films (10 minutes each) from the MEDSEACAN cruise were concatenated and encapsulated in order to obtain one video film corresponding to one dive to facilitate handling. Metadata from images captured during the Super Achille dives, like date, time and image name, were grouped manually in a distinct file in order to georeference these images via time codes within ArcGIS. Certain digital images were captured directly on board in real-time during the Super Achille dives. In addition, georeferenced minifilms were extracted with a 2 second image interval from the video films of the 2009 MARUM cruise and the 2011 MARUM-Senckenberg cruise. "Adelie" also allowed us to complete this image collection with georeferenced still images from the video films. The Geodesic system used was WGS84, in Mercator projection with standard parallel N42.

In this paper we focused on the occurrences of benthic fishes, Vulnerable Marine Ecosystems, and anthropogenic impacts located deeper than 180 m. Dive navigation tracks that occurred above 180 m depth were not considered.

2.4 Distribution of benthic megafauna species

In order to estimate abundances along navigation tracks each individual and colony record was plotted on the GIS and represented by a point. A video still of every record was captured and geo-referenced in a GIS when no digital image was available. Every specimen was identified at the lowest possible taxonomic level. However, identification at species level for some organisms from video footage was sometimes hampered due to poor video quality, high particle content in the water column and/or limited resolution for detecting morphological characteristics distinguishing similar species and had to be based on sampling. J. Vacelet (Marseille Univ.) assisted with Porifera identification, S. Sartoretto (Ifremer Toulon) and H. Zibrowius (Marseille) with cnidarian identification, E. Gramitto (ISMAR-CNR) with Actinopterygii Ophidiiformes identification, A. Souplet with Caridea identification and S. Iglesias (MNHN Paris) assisted with Actinopterygii identification.

2.5 *Distribution of substrates*

Two types of substrates could be seen in the video films: soft substrates and hard substrates. They were mapped along navigation tracks and the percentage per dive was calculated.

2.6 Distribution of bauxite red mud deposition

Every occurrence of red mud observed in the video films recorded in the Cassidaigne canyon was georeferenced and mapped.

2.7 Distribution of anthropogenic litter

In order to estimate abundances along navigation tracks, we focused on plotting occurrences of anthropogenic litter. They were classified into seven classes (metal, glass, plastic, pottery, wood, concrete, others - including fabric and paper-board) according to the method described previously (Spengler and Costa, 2008).

2.8 Quantification and distribution of trawling impacts and lost fishing gears

Trawling scars were counted along the navigation tracks when they were isolated and considered to be at least one meter in width. When they covered a large part of the navigation track with no possible individualization, the length of the disturbance was measured along the navigation track. Both types of trawling scar lengths were totalled and the percentage of the disturbance was calculated with regard to the total navigation track length of the dive. Lost fishing gears observed along navigation tracks were quantified and georeferenced.

2.9 Abundances (occurrence.km^{-1})

Evaluating surface areas and thus fauna densities from the video films was not possible technically, since: (1) the parameters (zoom, pan and tilt) of the camera used to record continuously were not steady; (2) the absence of lasers on the continuously recorded camera prevented the calculation of surfaces. In addition to these technical problems, the exploratory nature of the dives inevitably influenced the navigation tracks, introducing a bias in the data. Indeed, pilots and scientists tended to follow topographic features associated with fauna, which is completely different from following a pre-determined transect dedicated to the objective sub-sampling of spatial data.

With regard to these difficulties we decided not to calculate densities but to estimate abundances along navigation tracks. Event records per dive were extracted from the GIS distribution tables and their abundance was then standardized by dividing the counts by the length of the navigation track (calculated with the GIS tools). Each abundance was then calculated as a function of a one kilometer navigation track.

2.10 Abiotic parameters

The length of dive tracks was calculated using the Spatial Analyst Tool from ESRI GIS. Min. and Max. depths were extracted from navigation files or read on the video records when not available or incorrect in the navigation files.

The Euclidian distance to the coast was calculated in three steps. Firstly, each navigation track was reduced to its centre of gravity. The raster of the Euclidian distance to the closest coast line was generated and converted into a point shapefile. A spatial join between the two shapefiles (navigation track and distance to the closest coast) allowed calculating the distance to the closest coast for each navigation track.

The mean slopes for every navigation track were calculated in degrees from 0 to 90. A raster of the slopes was produced from the compiled bathymetry (100 m grid) of the Mediterranean Sea (Loubrieu and Satra, 2010). Polygons were created for each navigation track line using 70 m width buffers and converted into a raster shape file. A zonal statistics table generated by the Spatial Analyst Tool allowed summarising the mean slope values within the zone of another dataset, in our case the navigation track polygons.

2.11 Statistical analyses

Biogeographical analyses were performed on VME fauna and resource abundances averaged per canyon. Cluster analysis, non-metric Multi-Dimensional Scaling (nMDS) and Principal Component Analyses (PCA) were performed using PRIMER (Plymouth Routines in Multivariate Ecological Research, Ver. 5, (Clarke and Warwick, 2001)). Vertical distribution box plots and student t-tests were performed using R freeware.

We used Redundancy Analysis (RDA) in a multiple linear regression procedure in order to understand the effect of depth, slope and distance to the coast on the distribution of litter between canyons. RDA uses permutation testing to find the significance of explained variation (R freeware).

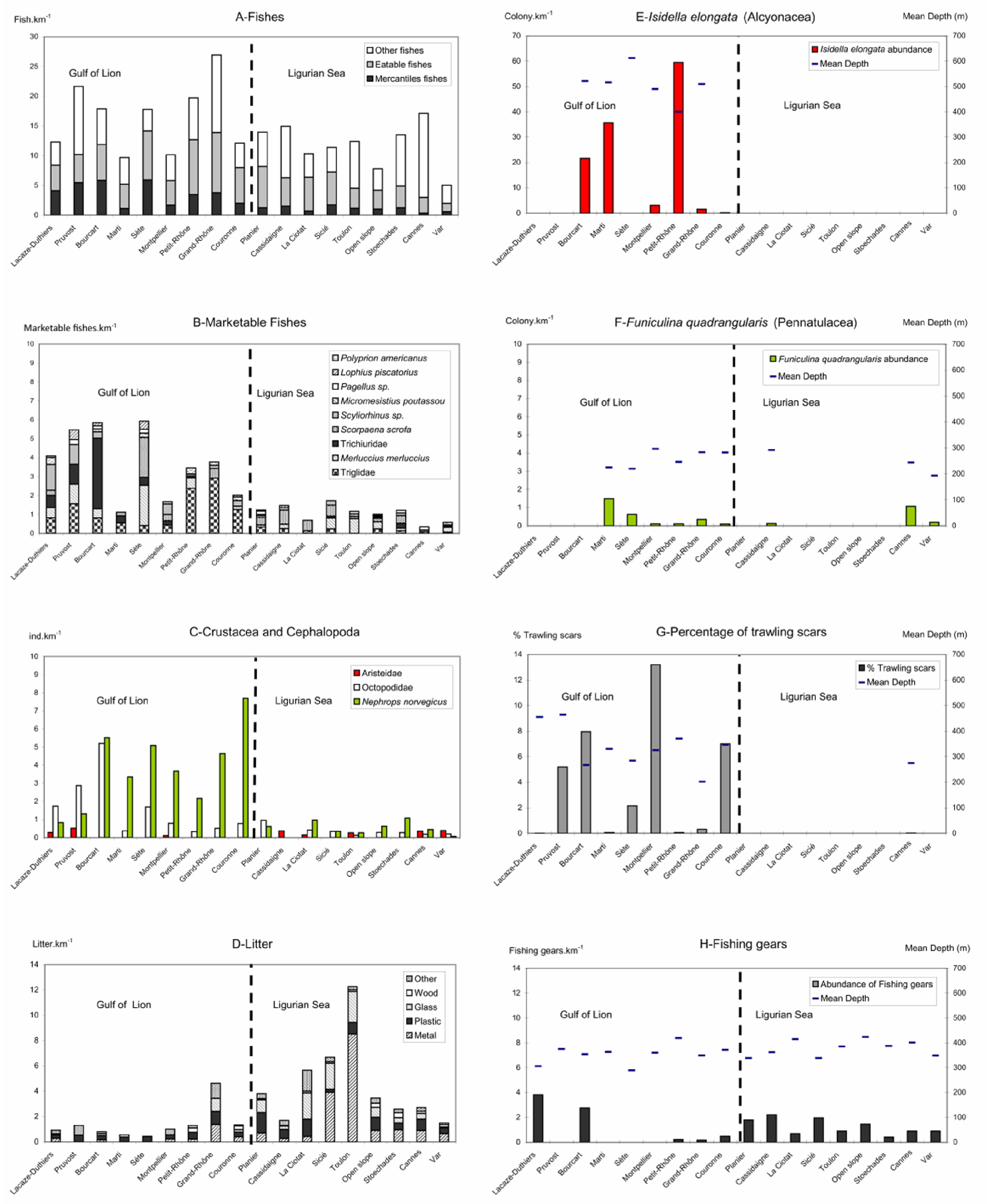

***Fig. 2**: Histograms of abundances.*
Selected taxa, litter and fishing impacts observed in the French canyons are shown from west to east.

3. Results

3.1 Distribution of fishing resources

3.1.1 Distribution and abundance of fishes observed on the seafloor

The fish species observed on the video films recorded along dive navigation tracks were listed with their abundance and maximum depth (Table 3). At least 59 mainly benthic and demersal species were recognized.

The most abundant species was *Helicolenus dactylopterus*, which was also the only species observed in every canyon. Two species were observed in shoals, *Trachurus* sp. and *Anthias anthias*, which were not counted and therefore removed from the following analyses. The other abundant species (>50 records for 101 dives) were *Coelorinchus caelorhincus*, *Phycis blennoides*, *Gadiculus argenteus*, *Capros aper*, *Galeus melastomus*, *Trigla lyra*, *Merluccius merluccius*, *Argentina sphyraena*, *Lepidorhombus boscii*, and *Scorpaena scrofa*.

Co-occurrences of fish species with vulnerable sessile marine species such as *Anthias anthias* were observed in shoals around bushes of *Madrepora oculata* in the Cassidaigne canyon, and *Benthocometes robustus* was observed only in the close vicinity of large colonies of gorgonians (*Callogorgia verticillata*) and antipatharians (*Leiopathes glaberrima* and *Antipathes* cf. *dichotoma*) up to 1 meter long in the Bourcart and Cassidaigne canyons.

The benthic fishes observed in the video films were classified into three categories: Marketable (M), Edible (E) and Others (O) (Table 3). Their abundance and distribution between canyons is presented in Fig. 2A. The distribution of marketable benthic fishes was analyzed in more detail as they are targeted by fisheries and their presence leads to impacts on the bottom caused by fishing.

3.1.2 Distribution and abundance of marketable benthic fishes

Of the 13 marketable fish species mentioned in table 3, we kept only 9 for the analysis. *Trachurus* sp. and *Zeus faber* were removed because one is pelagic and the other is from the shelf. *Scyliorhinus canicula* and *Scyliorhinus* sp. were grouped into *Scyliorhinus* spp. *Trigla lyra* and Triglidae were grouped into Triglidae. The 9 marketable fishes considered in the study are therefore *Lophius piscatorius*, *Merluccius merluccius*, *Micromesistius poutassou*, *Pagellus* sp., *Polyprion americanus*, *Scorpaena scrofa*, *Scyliorhinus* sp., Trichiuridae and Triglidae.

Triglidae were the most abundant, followed by *Merluccius merluccius*, Trichiuridae and *Scorpaena scrofa*. The Gulf of Lion (from Lacaze-Duthiers to Couronne) presents higher abundances of these marketable fishes than the Ligurian Sea (Student test, $p<0.0005$, variance equality), with two exceptions: the Marti and Montpellier canyons in which we observed fewer fishes (Fig. 2B).

3.1.3 Crustacea and Cephalopoda: Nephrops norvegicus*, Aristeidae and Octopodidae*

Nephrops norvegicus, a commercial crustacean, was found in every canyon explored apart from the Cassidaigne canyon (Fig. 2C). They were always observed defending their burrows against the ROV (Fig. 3A). The highest abundances were recorded in the Gulf of Lion in the Couronne canyon and Bourcart canyon. A total of 286 individuals were counted. They were located at a mean depth of 380 m (+/- 51 m).

Aristeidae, or red shrimps, were rarely observed in the videos (Fig. 3B). A total of 22 individuals were counted (Fig. 2C). They were located at a mean depth of 542 m (+/- 104 m). Shrimps of the Pandalidae family could be observed in higher abundance than Aristeidae, but they are not targeted by fisheries and are bycatch species.

Octopodidae were much more frequent in the Gulf of Lion than in the Ligurian Sea (Fig. 2C). The highest abundance was recorded in the Bourcart canyon. A total of 150 individuals were observed. They were located at a mean depth of 330 m (+/-81 m). Some individuals were very small, only 7 cm (Fig. 3C).

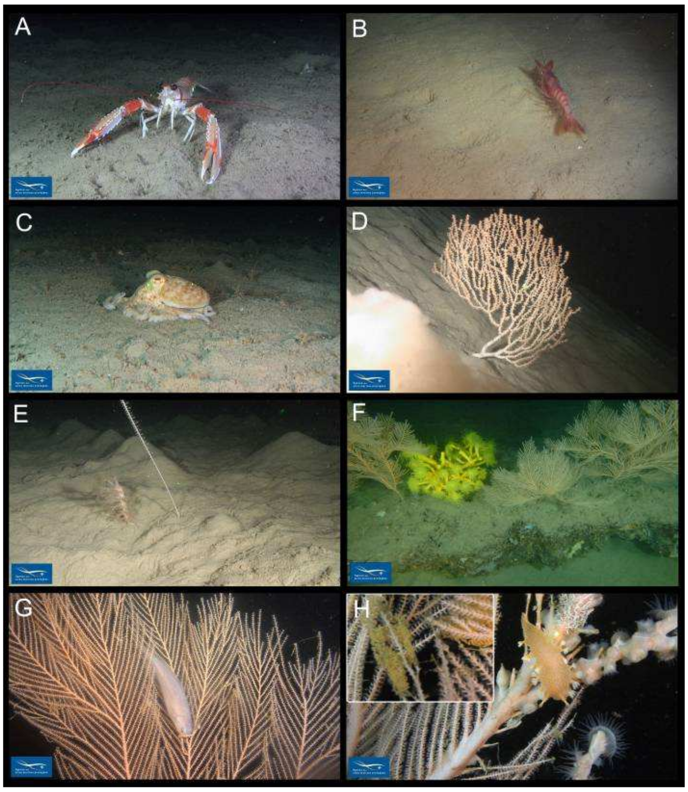

Fig. 3*: MEDSEACAN cruise images of commercial resources and vulnerable marine species.* ***A****: Nephrops norvegicus on bathyal bioturbated mud in the Planier canyon, dive P10, 395 m.* ***B****: A red shrimp, Aristeus antennatus, on bathyal mud in the Lacaze-Duthiers canyon, dive P13, 663 m.* ***C****: An example of Octopodidae on bathyal mud in the Couronne canyon, dive P1, 226 m.* ***D****: Isidella elongata on a sloping seafloor of compact mud in the Montpellier canyon, dive P3, 573 m.* ***E****: Funiculina quadrangularis (right) and Kophobelemnon leucharti (left) on bioturbated soft mud in the Marti canyon, dive P4, 227 m.* ***F****: Large colonies of Callogorgia verticillata and Dendrophyllia cornigera on a rocky slab in the Boucart canyon, dive BO_R2K_P1, 350 m.* ***G****: The Ophidiidae Benthocometes robustus hiding in a C. verticillata colony in the Bourcart canyon, dive BO_R2K_P1, 350 m.* ***H****: Nudibranchia Tritoniidae and the parasitic zoanthid Isozoanthus primnoidus living on a colony of C. verticillata; insert: detail of Tritoniidae eggs in the Sicié Canyon, dive P4, 261 m.*

3.2 Distribution of Vulnerable Marine Ecosystems

3.2.1 Distribution and abundance of Isidella elongata *communities observed on bathyal mud*

Isidella elongata colonies were observed in the Gulf of Lion during the MEDSEACAN cruise. They were found in higher abundance in three canyons: Bourcart (dive P5), Marti (P1 and P5), and Petit-Rhône (P3, P4 and P5) (Fig. 2E). A total of 913 colonies were counted. They were located at a mean depth of 459 m (+/- 84 m).

In the Bourcart canyon, colonies were observed between two gullies on the west flank (P5), with equal proportions of small (10/20 cm) and medium/large (40/60 cm) colonies. Trawling scars were also seen in this canyon, located on the other flank (P6).

In the two other canyons (Marti and Petit-Rhône) no trawling scars were seen where two meadows of *I. elongata* were present on sloping seafloor (about 10 to 20°) (Greene and Bizzarro, 2007). In the Marti canyon, all the colonies were small (20 to 30 cm high), while in the Petit-Rhône canyon (P5) large (60 cm) and small colonies (10/20 cm) could be observed close together, standing and healthy (Fig. 3D).

A few other colonies were observed in lower abundance in four canyons: Montpellier, Grand-Rhône, Couronne and Cassidaigne (one live colony and three dead ones in upright position, smothered with the red mud, MARUM 2009 cruise, dive D3).

The mud on which *I. elongata* colonies were established presented small domes or tumuli and holes, indicating a high level of bioturbation, mainly due to crustaceans. Many of these could be seen in the videos, including some Galathoidea (*Munida* sp.), Caridea (*Plesionika* sp.) and Axiidea (*Calocaris macandreae*), though the majority was made up of Nephropidae (*Nephrops norvegicus*). *I. elongata* was usually located on sloping seafloors (about 10 to 20°).

3.2.2 Distribution of Funiculina quadrangularis *communities on bathyal mud*

The highest abundance of *F. quadrangularis* was observed in the Marti canyon and in the Cannes canyon (Fig. 2F). A total of 32 colonies were observed at a mean depth of 239 m (+/- 31 m).

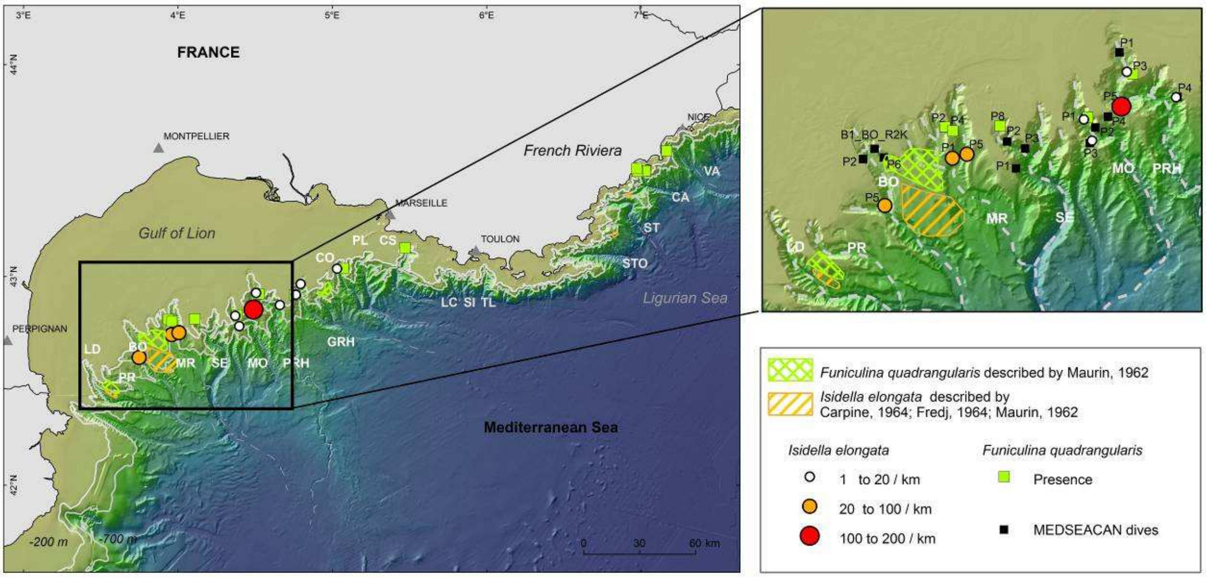

***Fig. 4**: Distribution of Isidella elongata and Funiculina quadrangularis observed during the MEDSEACAN dives in French canyons and as described by Maurin, 1962, Carpine, 1964 and Fredj, 1964.*

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.

3.2.5 Distribution of Callogorgia verticillata *communities observed on hard substratum*

The highest abundance was found in the Bourcart canyon (Dive _R2K_P1), followed by the Cassidaigne (P7, MARUM D2, D9), Planier (P8 and P11), Sicié (P4), Toulon (P4 and P5) canyons and on the open slope between Toulon and Stoechades (PO_P5) (Fig. 5). A total of 452 colonies were observed at a mean depth of 360 m (+/- 60 m).

In the Bourcart canyon we observed an exceptionally high density of the Primnoidae *C. verticillata* (Fig. 3F). The colonies were encountered on the eastern flank of the canyon, during the MEDSEACAN cruise dive BO_R2K_P1. About 400 colonies were seen forming a 900 meter line along a cornice. They were recorded by video (Fig. 5A). The cornice was a slab of hard substratum located at a depth of 350 m (Fig. 5B). The fan-shaped colonies were up to one meter in height and oriented perpendicular to the slope. They sheltered a high diversity of megafauna including: Porifera, Scleractinia (*Dendrophyllia cornigera*, *Desmophyllum dianthus* and *Madrepora oculata)*, Antipatharia (*Leiopathes glaberrima* and *Antipathes* sp.), Echinodermata (*Cidaris cidaris*, *Echinus melo* and *Echinus* sp.), Crustacea (lobster *Palinurus mauritanicus*, Caridea *Plesionika* sp. and Galatheoidea), Mollusca (Octopodidae), Actinopterygii (*Phycis blennoides*, *Phycis phycis*, *Lophius piscatorius*, *Helicolenus dactylopterus*, *Conger conger*, *Benthocometes robustus* and Trichiuridae), and Holocephali Chimaeridae (*Chimaera monstrosa*). Three individuals of the Actinopterygii *Benthocometes robustus* were observed hiding in *C. verticillata* fans with their heads pointing downwards (Fig. 3G). Evidence of fishing disturbance was observed many times with bottom lines and fishing nets hooked onto the hard cornice and damaging colonies of *C. verticillata*.

The Cassidaigne canyon is a semi-enclosed basin. Outside this basin, facing the abyssal plain on the open slope, a field of *C. verticillata* (43 colonies) was encountered during dive P7 (Fig. 5). The colonies, found at a depth from 390 to 350 m, were separated from each other by a distance from 3 to 4 meters. Dispersed colonies were also frequently encountered at depths of 200-294 m, specifically on rocky outcrops along spurs of the western flank of the Cassidaigne canyon (MARUM 2009 cruise, dives D2 and D9). Some live branches *of a C. verticillata* colony were covered by ophiuroids and crinoids, whereas on the basal stem, large aggregations of the serpulid *Filograna* sp. and sponges were present.

Few *C. verticillata* colonies were encountered in three other canyons (Planier, Sicié and Toulon) and on the open slope between Toulon and Stoechades, and always on raised slabs. Colonies were one to two meters high and accompanied by several species: pagurids, a comatulid crinoid (*Antedon* sp.), *Scorpaena scrofa*, a cnidarian (*Gerardia* sp.), a zoantharian (*Isozoanthus primnoidus*), and a tritoniid nudibranch that had laid its eggs on a gorgonian (see Fig. 3H).

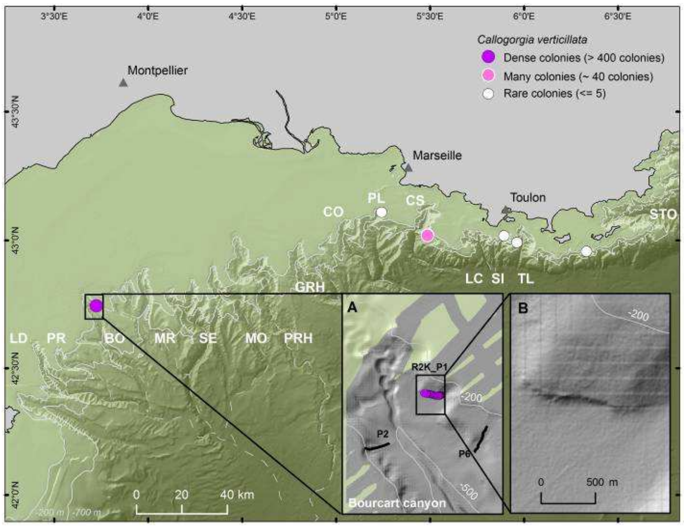

Fig. 5. *Spatial distribution of Callogorgia verticillata observed during the MEDSEACAN cruise.* ***A****: Zoom on the Bourcart canyon where dive BO_R2K_P1 took place.* ***B****: Zoom on the 900 m long cornice of hard substratum in the Bourcart canyon (350 m depth) where colonies of C. verticillata were aligned (see Fig. 3F).*

3.2.6 Distribution of cold-water coral communities observed on hard substratum

In the Mediterranean deep-sea two scleractinian species, *Lophelia pertusa* and *Madrepora oculata*, make up the dominant structure-forming corals (Fig. 6A).

The Lacaze-Duthiers canyon is the only French Mediterranean canyon where the two species *L. pertusa* and *M. oculata* have been observed living together in large quantities, the situation generally described for the biocoenosis of cold-water corals (CWC). In this canyon large colonies (> 40 cm) of both species of scleractinians were observed at depths ranging from 246 m to 541 m at the head of the canyon and its western flank during the MEDSEACAN and MARUM-Senckenberg 2011 cruises (Fig. 7A). This canyon was highly loaded in particles, making it difficult to analyse the video films.

On the western flank of the canyon the two species of scleractinians were observed during dives P15, D2, D6 and D7 aligned on edges at depths between 340 and 350 m. During dive P15, this edge was followed along an 800 m long navigation track and revealed medium-sized (20 to 40-cm in length), downward-growing colonies of *L. pertusa* and *M. oculata* (Fig. 6B). Toward the end of the dive, we encountered large (> 50 cm), healthy bushes of *L. pertusa* (Fig. 6C) covering an overhanging wall 10 m high and 20 m wide at 330 m depth on the western flank of the canyon (42°33.677' N, 3°23.940' E), on which many medium-sized colonies (around 20 cm) of *M. oculata* co-occurred. A considerable amount of coral rubble was partially buried in the sediment lying at the bottom of this wall. *M. oculata* was observed without *L. pertusa* (dives P2, P11, P15 and D5) on the same flank at shallower depths ranging from 246 to 325 m. On the same flank large, isolated bushes (> 50 cm) of *L. pertusa* were observed at deeper depths ranging from 507 to 541 m during dive P6, while only a few isolated colonies of *M. oculata* were encountered from 376 to 531 m depth.

On the eastern flank of the canyon, during dive P3, another edge of hard substratum was followed along 400 m at about 260 m depth. This edge created an overhang under which a series of *M. oculata* colonies were aligned growing downward. Few *L. pertusa* colonies were observed on this flank (six colonies during dive P3 and one colony during dive P14) and they were partly covered with particles and epibionts. A large number of old fishing lines were tangled on the edge and in the CWC frameworks. The top of the edge was covered with a continuous layer of sediment.

A considerable diversity of CWC associated species could be seen (Fig. 6D) in the Lacaze-Duthiers canyon. The fishes observed were mainly Actinopterygii represented by Macrouridae (*Coelorinchus caelorhincus*), Moridae (*Phycis blennoides*), Scorpaenidae (*Helicolenus dactylopterus*) and Trichiuridae. Some Elasmobranchii were also present with Carchariniformes (*Scyliorhinus canicula*) and Squaliformes (*Oxynotus centrina*). Echinoidea (*Cidaris cidaris, Echinus melo, Gracilechinus acutus*), Scleractinia (*Desmophyllum dianthus, Dendrophyllia cornigera*), Bivalvia (*Neopycnodonte cochlear*), Porifera (*Poecillastra compressa, Hamacantha falcula,* and others), Crustacea (Paguroidea and Galatheidae) and Ascidiacea were numerous in these ecosystems. Some Comatulida (*Leptometra phalangium*) were observed on an old fishing line trapped on the bottom. No Antipatharia were observed during the dives carried out in the Lacaze-Duthiers canyon.

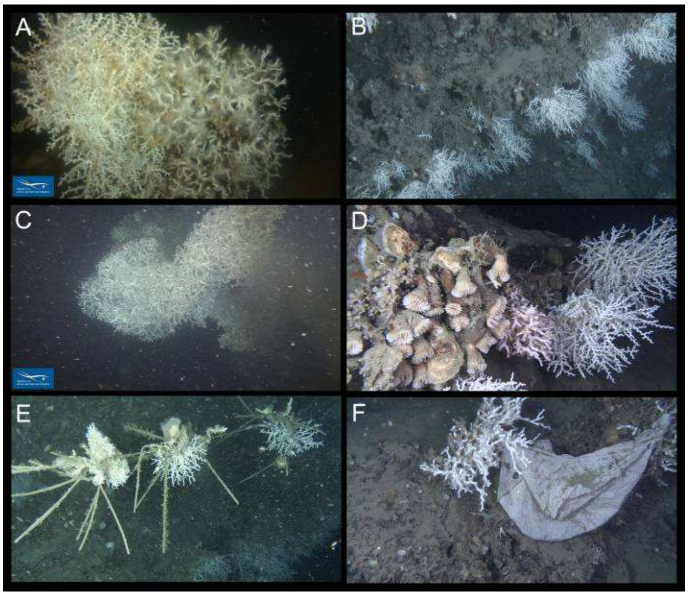

Fig. 6. *Cold-water Corals in the Lacaze-Duthiers canyon.*
A*: Colonies of Madrepora oculata (left) and Lophelia pertusa (right), MEDSEACAN cruise , dive P15, 369 m.* ***B****: Colonies of M. oculata growing downward, MARUM-Senckenberg cruise, dive D7, 342 m.* ***C****: Large colonies of L. pertusa covering a vertical cliff and growing horizontally, MEDSEACAN cruise, dive P15, 343 m.* ***D****: Communities of M. oculata and L. pertusa colonies together with Desmophyllum dianthus and Neopycnodonte cochlear specimens, MARUM-Senckenberg cruise, dive D6, 387 m.* ***E****: Lost long line under tension serving as substrate for sabellids, serpulids (amongst Filograna sp.), L. pertusa and Neopycnodonte cochlear, MARUM-Senckenberg cruise, dive D2, 331 m.* ***E****: Soft plastics entangled in L. pertusa causing necrosis in area of contact, MARUM-Senckenberg cruise, dive D6, 468 m.*

The second CWC location in the area studied was the western flank of the Cassidaigne canyon. *M. oculata* seems to be the only structure-forming scleractinian as *L. pertusa* has never been recorded in this canyon.

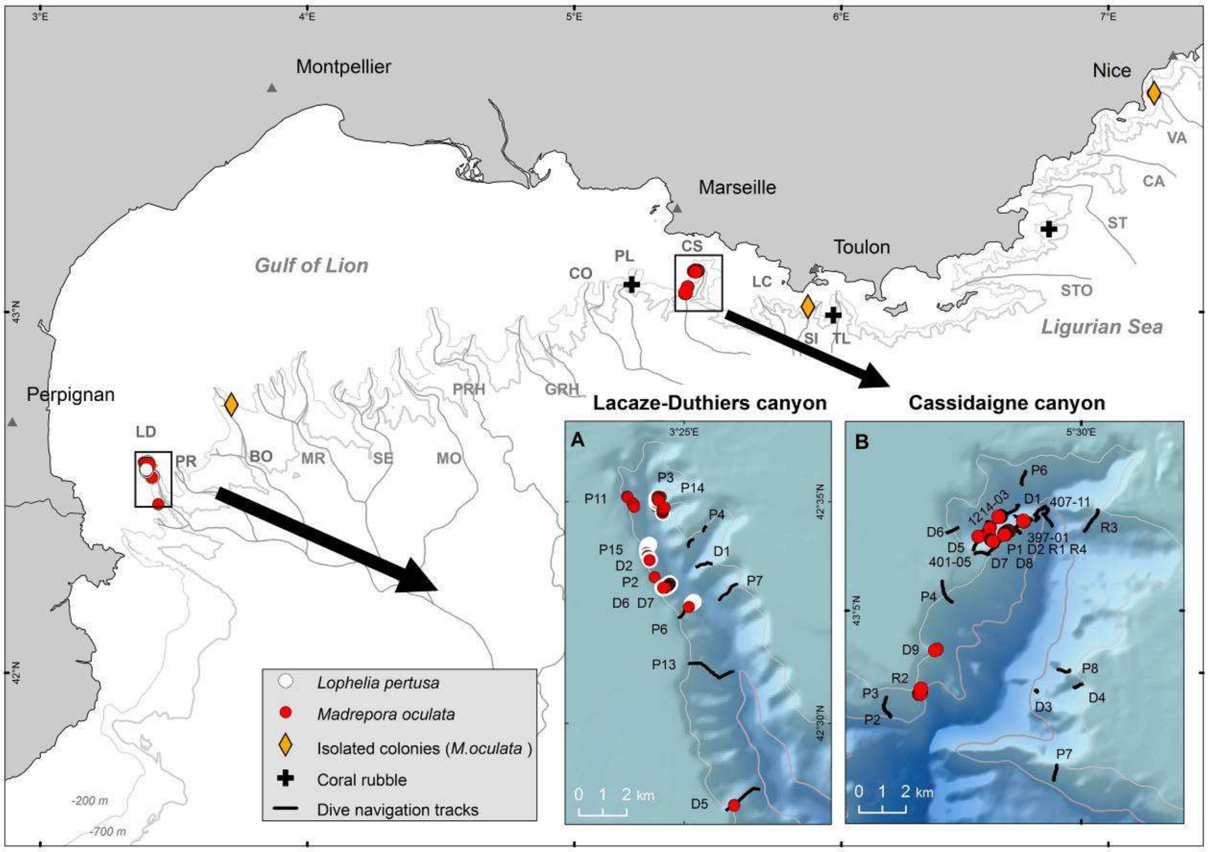

***Fig. 7**: Distribution map of frame-building scleractinian cold-water coral communities.*
***A**: Zoom on the Lacaze-Duthiers canyon. **B**: Zoom in the Cassidaigne canyon.*

The largest concentration of *M. oculata* colonies was observed on the west flank of the canyon along a crest (43° 06.76' N; 5° 27.62' E) during MEDSEACAN dive P1, MARUM 2009 dive D2, R1, R4 and ESSROV 2010 dive 401-05 at depths ranging from 200 to 210 m (Fig. 7B). At this location at the edge of the shelf, the velocity of the bottom current and the diversity were higher than what could be seen on the shelf above. The bedrock showed characteristic features of a formerly karstified landscape with dissolution holes forming cave galleries separated by pillars (Fig. 8A). The rugged topography of this karstified spur caused the loss of many fishing gears (Fig. 8B). Large bushes of *M. oculata* were observed covering the substratum whose relief was extremely rough below the overhangs (Fig. 8C). Mature *M. oculata* colonies attained heights up to 40 cm. *M. oculata* co-occurred with many Porifera (*Poecillastra compressa* and others that could not be identified on the video films), Antipatharia (*Leiopathes glaberrima*, *Antipathella subpinnata, Antipathes* cf. *dichotoma*), Scleractinia (*Dendrophyllia cornigera*), Alcyoniina (*Gersemia* sp.), Ophiuroidea (*Astrospartus mediterraneaus*), Echinoidea (*Cidaris cidaris*, *Echinus melo*), Crustacea (Brachyura), Bivalvia (*Spondylus gussoni*) and Actinopterygii (*Anthias anthias*, *Conger conger*, *Helicolenus dactylopterus*). At this site at 210 m depth, *M. oculata* could be seen mixed with species from circalittoral depths, such as Holaxonia (*Eunicella cavolini*, *Paramuricea clavata*) and Scleraxonia (*Corallium rubrum*) (Figs. 8D and 8E).

M. oculata could be observed in red mud below 350 m (see 3.3.6) (Table 1 and 2) on the north face of the edge during dives 1214-03, 397-01, D5, D7, D8 and R1.

Further south in the canyon, still on the west flank, a peculiar spot was discovered during dive R2. This was a vertical escarpment descending from 320 m depth down to at least 480 m. The wall was colonised locally by recently settled dense colonies of *M. oculata* with very fragile branches hardly exceeding 4 cm in length. During dive D9, two small healthy colonies of *M. oculata* were observed at 324 and 244 m depth fixed on a vertical wall on which could also be seen colonies of *Leiopathes glaberrima* and *Corallium rubrum*.

The giant deep-sea oyster, *Neopycnodonte zibrowii*, was frequently encountered on (sub-) vertical flanks and overhangs of bedrock exposed in the 376-470 m depth range and appeared to be fossilised during dives D1, D7 and D9.

During the MEDSEACAN cruise, previously non reported occurrences of *M. oculata* were observed in three other canyons: Bourcart, Sicié and Var (Fig. 7, orange diamonds). In the Bourcart canyon, *M. oculata* was observed on a shelf of hard substratum at 331 m depth, during dive BO_R2K_P1 (42°44.688 N, 3°42.953 E). Several single branches protruded from a slab. In the Sicié canyon a 15-cm colony of *M. oculata* was observed at 255 m depth (43° 0.873 N, 5° 52.501 E) while in the Var canyon, three young branches 2 cm long were seen growing at 350 m depth on a wall of hard rock (43°35.868 N, 7°9.863 E).

Several broken fragments of dead cold-water corals, probably *M. oculata*, were seen in the Planier canyon (Dive P3) (Fig. 7, black crosses) but could not be collected. They were located at the bottom of a cliff.

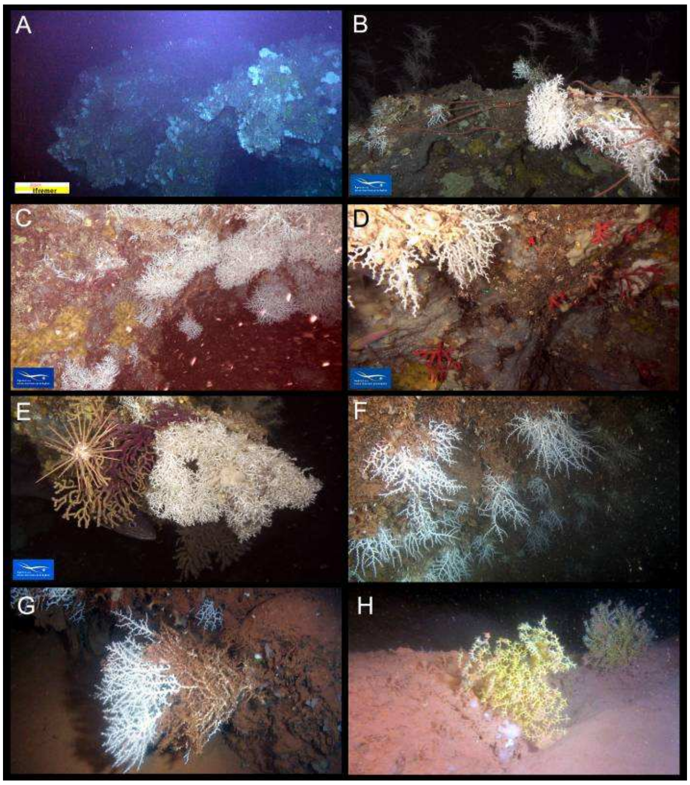

***Fig. 8**: Madrepora oculata and red mud deposits in the Cassidaigne canyon.*
***A**: Characteristic features of the bedrock covered with M. oculata colonies, ESSROV 2010 cruise, dive 401-05, 238 m. **B**: Lost fishing gears entangled with M. oculata bushes in the Cassidaigne canyon, MEDSEACAN cruise, dive P1, 200 m. **C**: Several white bushes of M. oculata growing downward from a rocky overhang, dive P1, 205 m. **D**: Red coral Corallium rubrum colonies co-occurring with M. oculata colonies, MEDSEACAN cruise, dive P1, 210 m. **E**: High species diversity associated with M. oculata colonies: Cidaris cidaris, Paramuricea clavata and Conger conger hiding below a coral framework, MEDSEACAN cruise, dive P1, 205 m. **F**: M. oculata colonies with elongated shapes and thin axes regularly spaced on a wall covered with red mud, MARUM 2009 cruise, Dive D5, 365 m. **G**: M. oculata colonies with*

basal portions lacking coral tissue colonised by epibionts like hydrozoans and covered with red mud, MARUM 2009 cruise, dive D7, 464 m. ***H****: Fan-shaped current facing colonies of Acanthogorgia hirsuta fixed on a rocky slab covered with red mud, MARUM 2009 cruise, Dive D1, 470 m.*

3.3 *Distribution of Vulnerable Marine Ecosystem (VME) fauna and anthropogenic impacts*

3.3.1 Distribution of trawling scars on bathyal mud

Trawling scars were mainly located in the Gulf of Lion (Fig. 2G). We observed some large areas of sediment completely impacted (alternatively smoothed and ploughed) by repeated trawling in five canyons: Pruvost, Bourcart, Sète, Montpellier and Couronne. A highly impacted area 800 m long was observed in the Montpellier canyon, representing 43% of the navigation track (Fig. 13A). Trawling scars were located at a mean depth of 330 m (+/- 64 m).

3.3.2 *Analysis of the spatial distribution* of *resources and VME fauna on bathyal mud*

The hierarchical classification of canyons with regards to their composition in resources (marketable fishes, *Nephrops norvegicus*, Octopodidae) and VME fauna (*Funiculina quadrangularis*, *Isidella elongata*) on bathyal mud shows that two groups of canyons are separated at a similarity threshold of 45%: the Gulf of Lion and the Ligurian Sea.

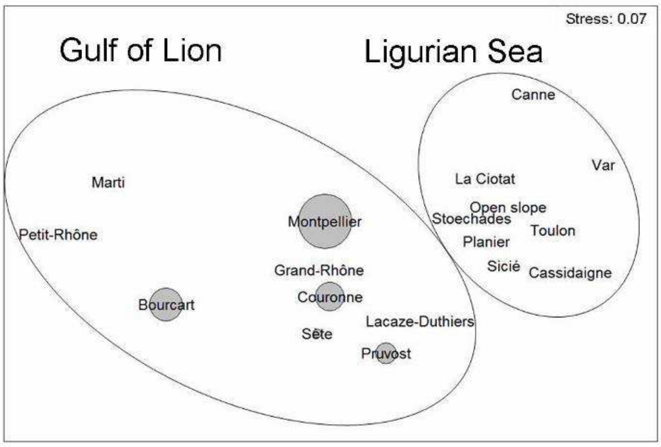

Fig. 9. *Non metric, multi-dimensional scaling ordination of canyons. Bray-Curtis similarity coefficients of resources and VME fauna abundances were used for the ordination. Clusters formed at the 45% similarity level and trawling impact represented by circles of different sizes were superimposed on the MDS plot.*

A non-metric, multidimensional scaling (nMDS) plot was produced by PRIMER (Fig. 9). A stress value of 0.07 was derived by statistical processing, indicating good ordination. A cross-check against the results of hierarchical classification was made by superimposing the groups having similarities of 45%, corresponding to the Gulf of Lion and the Ligurian Sea. The superimposition of trawling scar abundances highlights the fact that bottom trawling occurs only in the canyons of the Gulf of Lion.

A Principal Component Analysis (PCA) was performed to ordinate canyons with regarding their abiotic environmental parameters that had been normalised beforehand: percentage of mud and mean slope encountered along navigation tracks. The first principal component axis explains 85% of the variance between canyons and is driven by the percentage of mud.

The Gulf of Lion canyons are characterised by muddy substrates, while the Ligurian Sea canyons are characterised by hard substrates. The Lacaze-Duthiers canyon, which is in fact located in the Gulf of Lion, is represented in the Ligurian Sea canyons group, illustrating the high percentage of hard substrate in this canyon.

3.3.3 *Vertical distribution of resources, VME fauna and the impact of trawling on bathyal mud*

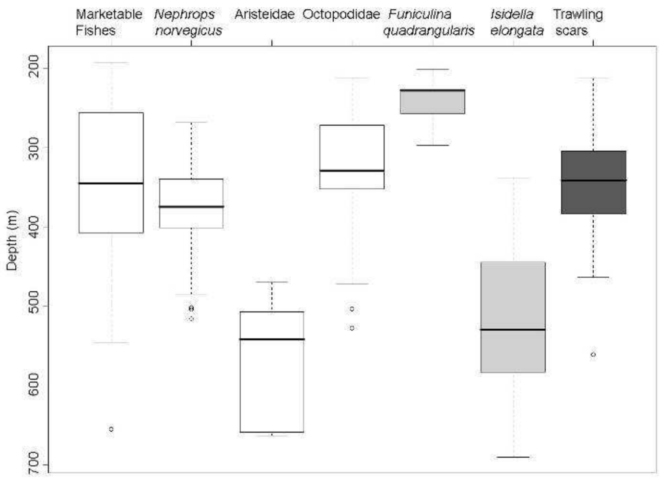

Fig. 10. *Box-plot of vertical distributions in the Gulf of Lion.*
Resources (white), VME fauna (light grey) and trawling impact (dark grey) observed on bathyal mud in the French canyons of the Gulf of Lion during the MEDSEACAN dives.

The vertical distribution of *Isidella elongata* and *Funiculina quadrangularis* was compared to the one of resources and trawling scars in the Gulf of Lion (Fig. 10). Specimens of *F. quadrangularis* were located at shallower depths (240 m) than trawling scars (355 m) whereas specimens of *I. elongata* were located at deeper depths (516 m) (Student tests show significant differences for both, $p<0.05$). There was no statistical difference between depth of trawling scars and resources [marketable fishes ($p=0.30$), *Nephrops norvegicus* ($p=0.10$) and Octopodidae ($p=0.36$)]. Aristeidae were located deeper (564 m), in the same range as *I. elongata* (516 m) (Student test show no significant difference, $p=0.21$).

3.3.4 Distribution of lost fishing gears on hard substratum

Lost fishing gears could be observed in every canyon of the Ligurian Sea (from Planier to Var canyons) and in five canyons of the Gulf of Lion (Fig. 2H). They consisted of lost nets, lead weights and ropes, damaging structure-forming fauna and breaking cnidarian colonies. Long lines were often entangled around rocky obstacles and under tension. They formed an artificial substrate which was preferentially colonised by sabellid and serpulid polychaetes, and occasionally by *Neopycnodonte cochlear* and scleractinian corals (Fig. 6E). The highest abundances were recorded in the Lacaze-Duthiers, Bourcart (Fig. 2H) and Cassidaigne canyons (Fig. 13B). A total of 199 lost fishing gears were counted at a mean depth of 343 m (+/- 88 m).

3.3.5 Analysis of the vertical distribution of VME fauna and lost fishing gears on hard substratum

The vertical distribution of *Callogorgia verticillata*, *Lophelia pertusa* and *Madrepora oculata* was compared to that of marketable fishes and fishing gears in the Lacaze-Duthiers, Bourcart and Cassidaigne canyons (Fig. 11). *C. verticillata* was located within a very narrow depth range around 340 m. *L. pertusa* was found deeper than *M. oculata* (the Student test shows significant difference,

$p<0.05$). There was no statistical difference between depth of fishing gears and marketable fishes ($p=0.11$) or *C. verticillata* ($p<0.05$). On the contrary, fishing gears, *L. pertusa* and *M. oculata* were found at different mean depths (Student tests show significant differences, $p<0.05$), but their bathymetric ranges overlapped.

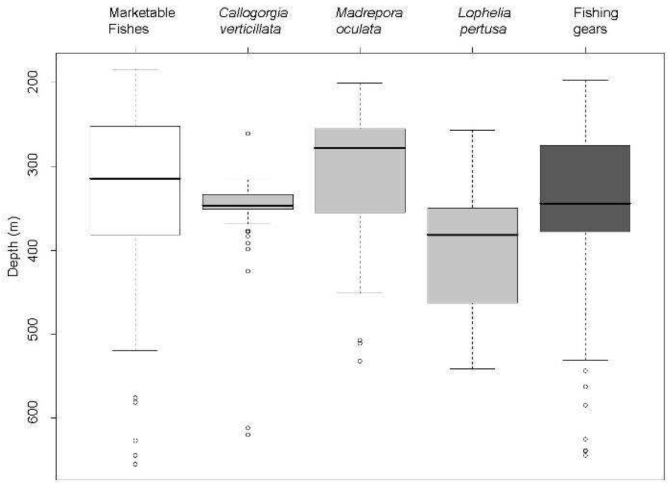

Fig. 11. *Box-plot of vertical distributions in the Lacaze-Duthiers, Bourcart and Cassidaigne canyons.*
Resources (white), VME fauna (light grey) and fishing gears (dark grey) observed during the MEDSEACAN dives on hard substratum in the Lacaze-Duthiers, Bourcart and Cassidaigne canyons.

3.3.6 Distribution of cold-water coral and bauxite red mud deposits in the Cassidaigne canyon

During all the dives in the north of the Cassidaigne canyon we observed a continuous thick layer of red mud below 350 m depth (Fig. 12). In the area affected by the red mud, *Madrepora oculata* was present in water depths from 365 to 515 m depth (dives D5, D7, 397-01 and 1214-03).

Dense bushes of *M. oculata* were recorded between 515 and 485 m depth (dive 1214-03) (Fig. 12) on a vertical cliff in the northern part of the western gully. A large overhang at the summit of the cliff (5 m wide) was covered with red mud. The Cyana submersible followed the edge of the overhang for 10 minutes and dense bushes of *M. oculata* could be observed growing from the edge.

In the western gully, *M. oculata* could be observed (D5) at 365 m depth on a vertical wall 5 m high, slightly covered with red mud. The colonies on this wall were regularly spaced, had elongated shapes with thin axes (Fig. 8F) and grew horizontally or downwards. They seemed to have settled recently. A dozen white colonies were also observed on a small rocky slab completely covered with red mud at 466 m depth (D7) (Fig. 8G).

Along the rocky edge at depths ranging from 300 to 390 m, sparse bunches of *M. oculata* were recorded on small rocks emerging from the substrate covered with red mud (dives 397-01 and R1).

Below 350 m depth hard substrates were colonised by live solitary corals, including *Desmophyllum dianthus* and *Caryophyllia calveri*, with scattered to abundant frequencies and individuals measuring up to 5 cm in length. The upper portions and the flanks of the outcropping hard rock served as substrate for mainly fan-shaped, current-facing *Acanthogorgia hirsuta* colonies measuring up to 30 cm in length (Fig. 8H). Frequently, branches of soft corals and basal portions of solitary corals were also covered with red mud. The sponge *Tetrodictyum* cf. *tubulosum* was also observed in higher abundance in this red mud environment than in other parts of this canyon. The sponge *Farrea* sp. was also observed at this location but nowhere else in our study. Lower in the canyon (dive 407-11) a layer of fossil bivalves (*Neopycnodonte zibrowii*) was observed to play the role of a hard substrate for solitary corals. Further down, at the bottom of the canyon (725 m), we found a thick layer of red mud so fluid that the ROV could not settle on the bottom to operate sampling tools (). No life could be seen on the muddy bottom.

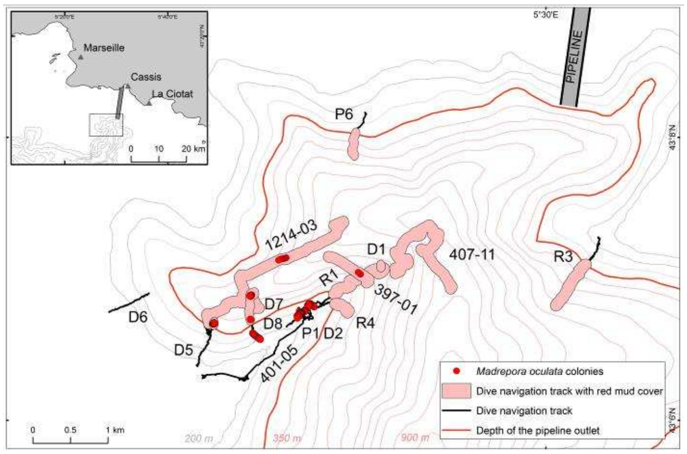

Fig. 12. *Distribution map of Madrepora oculata and red mud cover observed during dives in the Cassidaigne canyon.*

3.3.7 Distribution of anthropogenic litter

The highest abundance of litter was observed in the Toulon canyon in the Ligurian Sea (up to 12 items.km^{-1}), while the highest abundance in the Gulf of Lion was observed in the Grand-Rhône canyon (up to 5 items.km^{-1}) (Fig. 2D). The canyons subject to less impact were the Sète and Marti canyons in which almost no debris was observed, except for plastics (100% in the Sète canyon) (Fig. 6F). The mean abundance was 3 items per km, 5 in the Ligurian Sea, and 1 in the Gulf of Lion.

The highest abundances of metals were found in the Toulon (9 items.km^{-1}) and Sicié (4 items.km^{-1}) canyons (Fig. 13C). Plastics were observed in every canyon, with the highest abundance occurring in the Planier canyon (2 items.km^{-1}) (Fig. 13D). Glass litter was observed eastwards from the Grand-Rhône (1 items.km^{-1}) to the Var canyons in the Ligurian Sea, with a peak in the Toulon (2 items.km^{-1}), La Ciotat (2 items.km^{-1}) and Sicié (2 items.km^{-1}) canyons. Wood debris was mainly located in the Stoechades canyon (0.4 items.km^{-1}) and on the Open slope (0.3 items.km^{-1}). Concrete, ceramics and other litter (fabrics and paper-board) were grouped together because they were not represented significantly.

Redundancy Analysis in the multiple linear regression procedure detected that the "Distance to the coast" variable accounted for 17% of the variance in the distribution of litter between canyons (p-value = 0.055). Mean depth, mean slope and navigation length did not provide a significant explanation of the distribution of litter between canyons.

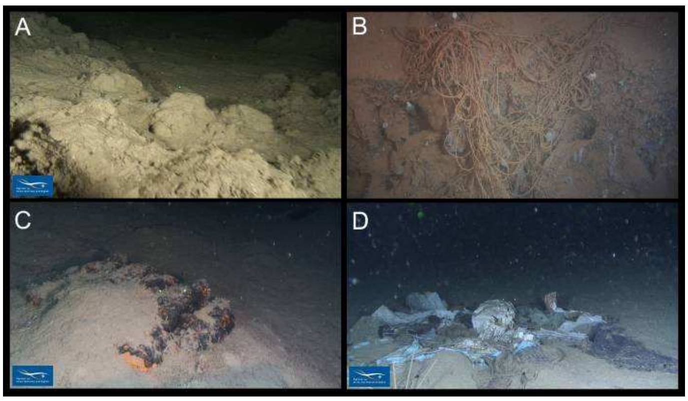

Fig. 13*: Anthropogenic impacts in canyons.*

A*: Bathyal mud ploughed by trawling in the Montpellier canyon, MEDSEACAN cruise, dive P4, 374 m.* ***B****: Fishing lines trapped on a rocky escarpment in the Cassidaigne canyon in an area* *of bauxite red mud sedimentation, MARUM 2009, dive D7, 465 m.* ***C****: Metal litter (munitions) in the Toulon canyon, MEDSEACAN cruise, dive P5, 495 m.* ***D****: Accumulation of soft plastic litter in the Planier canyon, MEDSEACAN cruise, dive P8, 397 m.*

4. Discussion

4.1 Distribution of benthic fishing resources and trawling impact

Fishing resources (marketable fishes, crustaceans and cephalopods) were statistically more abundant in the Gulf of Lion than in the Ligurian Sea. This result further supports the well-known fact that the Gulf of Lion is an area of high productivity compared to the other parts of the Mediterranean Sea (Cartes et al., 2004). The amount of organic carbon enhancing the food chain results from the arrival of cold and fresh water from the Rhône River, bringing organic and inorganic matter from continental sources into the Gulf of Lion. The organic-matter-rich-sediment is intercepted by the heads of shelf-incising canyons and transported down-slope where it provides food to benthic ecosystems (Coll et al., 2010; Danovaro et al., 2010). Another factor that can explain the high concentration in fishing resources in the Gulf of Lion is the consequence of its large continental shelf and exposure to a cold and intense northern wind (Mistral), causing seasonal cooling and evaporation leading to the formation and downwelling of dense surface sea-water.

The benthic fishes that were recognised in the video footage of this study are those that have been frequently described on the upper slopes of the western Mediterranean Sea in previous studies in which species were sampled by trawling, as in the "MEDiterranean International Bottom Trawl Survey" (MEDITS) project (Bertrand, 2002; Cartes et al., 2002; D'Onghia et al., 2004; Demestre et al., 2000; Morfin et al., 2012). Optical imagery is a reliable tool for evaluate fish diversity, although it is not efficient for stock assessment because of difficulties in estimating spatial density and due to the escape behaviour of mobile species.

Nephrops norvegicus is a commercially important crustacean in the Mediterranean Sea. It is a sedentary marine decapod known for its burrowing behaviour and dependence on the muddy seabed sediments of the slope (Mytilineou and Sarda, 1995; Sarda, 1998). Their higher abundance in the Gulf of Lion is probably due to their preference for fine-grained sediment environments with weak hydrodynamics (Maynou and Sarda, 1997; Tully and Hillis, 1995).

Several species of Octopodidae were observed in the video films though their identification was not possible without sampling. The common octopus (*Octopus vulgaris*) and the horned octopus (*Eledone cirrhosa*) are commercially important in the Mediterranean Sea and are caught by trawling either on the continental shelf for juveniles or at greater depth for larger individuals (Sanchez et al., 2004). Octopodidae were generally located in the Gulf of Lion. The highest abundance observed in the Bourcart canyon is probably due to the rocky slab providing potential hiding and nesting places. Species living on soft bottoms are probably different from those living in a rocky environment.

We assume that most of the specimens of Aristeidae encountered might be *Aristeus antennatus,* which was often sampled during the MEDITS programme in the Gulf of Lion (Cau et al., 2002). Aristeidae were located deeper and in lower abundance than other resources. These depths (< 500 m) were explored by less than half of the MEDSEACAN dives, which could explain the low abundance in Aristeidae observed in this study. Moreover Aristeidae have been observed previously down to 3000 m in the Balearic Islands (western Mediterranean Sea) (Cartes et al., 2009; Sarda et al., 2004). The variability in the vertical distribution of *Aristeus antennatus* has been proved to be correlated to the strong currents occurring during intense cascading events (DSWC) that displace individuals towards greater depths over a ten-year time-scale (Company et al., 2008).

Other shrimp, such as the bentho-pelagic species *Plesionika* spp., were recorded in the video films during the MEDSEACAN cruise. They were often located in high abundance in trawling scars where no other benthic species could be seen. This is explained by the fact that these opportunistic shrimp move into the trawling lane as a result of the temporary increase in food occurring due to the increased mortality of organisms following the passage of trawls (Dimech et al., 2012; Ramsay et al., 1998).

Trawling impacts were seen to occur in the same depth-range as marketable fishes, *Nephrops norvegicus* and Octopodidae, which led us to assume that these species are targeted by bottom trawling. Nevertheless, as Aristeidae are probably located deeper than the area explored, we could not conclude on their "targeted species" status. In some other areas of the western Mediterranean Sea, bottom trawling targeting the deep sea shrimp *Aristeus antennatus* is so intense that it has modified the morphology of the sea floor above 800 m (Martín et al., 2013; Puig et al., 2012).

4.2 Distribution of Vulnerable Marine Ecosystem (VME) and anthropogenic impacts

Vulnerable Marine Ecosystems (VME) have been defined by OSPAR and the European Commission as being any marine ecosystem whose integrity (i.e. ecosystem structure or function) is, according to the best scientific information available and to the principle of precaution, threatened by significant adverse impacts resulting from physical contact with bottom gears in the normal course of fishing operations. Such ecosystems include, inter alia, reefs, seamounts, hydrothermal vents, cold-water corals and cold-water sponge beds. The most vulnerable ecosystems are those that are easily disturbed and whose recovery is either slow or impossible (European Commission, 2008). Bottom trawling and long lines have been shown to have dramatic effects on the structure and functioning of deep-sea ecosystems (Auster et al., 2011).

4.2.1 Isidella elongata *communities and trawling impact on bathyal mud*

We encountered few meadows of *I. elongata* in the Gulf of Lion (Bourcart, Marti and Petit-Rhône), although these communities were frequently referenced in the past in the Mediterranean Sea where they were described on the compact mud of the middle slope horizon between 500 and 1200 m depth (Bellan-Santini et al., 2002; Cartes et al., 2004; Peres and Picard, 1964; Relini-Orsi and Relini, 1972).

Trawling scars were always seen at shallower depths than those of *I. elongata* colonies. We never observed any overlap between the two vertical distributions. This led us to assume that *I. elongata* has been swept away by repeated trawling in the shallowest part of its natural distribution. This gorgonian species has practically disappeared from the Mediterranean Sea as it grows in areas targeted by trawling (Cartes et al., 2009; Maynou and Cartes, 2012). Deep-water gorgonian corals are known to grow slowly and live for hundreds of years (Risk et al., 2002; Williams et al., 2007), which implies a long recovery time. Anthropogenic disturbance by trawling is thus devastating for these meadows of *I. elongata*. They are considered as a sensitive habitat and efforts are being made to give them protected status (GFCM, 2009a).

The highest density of *I. elongata* was located on a sloping seafloor (approx. 10 to 20°) in the Petit-Rhône canyon. We assume that slopes provide protection from bottom trawling which cannot be performed on sloping seafloors. Depth also provides protection from trawling, which is limited to 1000 m in the Mediterranean Sea (Sacchi, 2008). The sloping seafloor and deep seabed down to 1800 m on which *I. elongata* was observed during other cruises (M-C. Fabri, pers. obs.), may act as refuge areas for this species. These refuge areas could be seen as locations where gorgonians could reproduce and disseminate. Nevertheless, no study has been conducted to assess their potential dispersion. Existing data on the growth rates of isidid octocorals are scarse but indicate slow annual growth (Andrews et al., 2009).The life span of Isididae can reach 400 years (Sherwood et al., 2009). Little is known about other important life history aspects of Isididae, such as reproduction, dispersal and colonisation patterns.

Historical data suggest that *I. elongata*'s preferential habitat may be between gullies rather than in canyons, a characteristic we observed three times during the MEDSEACAN cruise. Large meadows of *I. elongata* were described in 1962 and 1964 between canyons (Carpine, 1964; Fredj, 1964; Maurin, 1962) (Fig.4). As the objective of the MEDSEACAN cruise did not focus on these areas, they should be considered as an objective for a future cruise in order to check the actual condition of these meadows and complete the present distribution of the species.

4.2.2 Funiculina quadrangularis *communities and trawling impact on bathyal mud*

We observed few *F. quadrangularis* in the video films. They were mainly located in the upper part of the explored area. This Pennatulacea is known to characterise the upper slope horizon in the soft muddy sediment between 180 and 400 m depth in the Mediterranean Sea (Bellan-Santini et al., 2002; Cartes et al., 2004; Peres and Picard, 1964).

The inability of *F. quadrangularis* to withdraw into the sediment makes it sensitive to physical disturbance (MacDonald et al., 1996). It is thought that this sea-pen has already disappeared from many trawling locations. Indeed the commercial Norway lobster *Nephrops norvegicus* occupies the same deep mud biotopes as Pennatulacea (Cartes et al., 2004). Trawls designed for *N. norvegicus* scrape the seabed, removing emergent epifauna and leaving it flattened. The effect of trawling on the sensitive *F. quadrangularis* makes it vulnerable. Although these Pennatulacea and their associated habitats are not directly protected by legislation they are considered to be as "sensitive" habitats worthy of conservation and more should be known about their distribution (GFCM, 2009a).

Trawling scars were always seen deeper than *F. quadrangularis* colonies. This led us to assume that either *F. quadrangularis* has been swept away by repeated trawling in the deepest part of its natural distribution, or it is located on the continental shelf as observed during the MEDITS cruise in 2012 (A. Jadaud, pers. comm.).

Historical data suggest that the preferential habitat of *F. quadrangularis* could be located between gullies rather than in canyons. Large meadows of *F. quadrangularis* were described between canyons in 1962 (Carpine, 1964; Fredj, 1964; Maurin, 1962) (Fig.4). As the objective of the MEDSEACAN cruise did not focus on these areas, they should be considered as an objective for a future cruise in order to check the actual condition of these meadows and complete the present distribution of the species.

4.2.3 Callogorgia verticillata *communities and lost fishing gears on rocky substrates*

Callogorgia verticillata is an Alcyonacea that grows to a height of 1 m (Bo et al., 2012). It is a suspension feeder forming large fans (1 m wide) oriented in the direction of the predominant current and mainly observed on rocky outcrops (Sanchez et al., 2009). This species is often seen associated with species of epifauna not observed in other communities, making this association unique (Ophidiiformes *Benthocometes robustus*, Nudibranchia Tritoniidae, zoanthid *Isozoanthus primnoidus*). The parasitic zoanthid *Isozoanthus primnoidus* (Carreiro-Silva et al., 2011) was observed on a single colony in the Sicié canyon, whereas it has been observed more frequently in the Azores (Carreiro-Silva et al., 2011). This zoanthid does not appear to be a threat for gorgonians.

The Bourcart canyon holds a particularly rich population of these colonies on a 900 meter long cornice. This cornice was irregularly shaped as if covered by biogenic concretions, probably formed when the level of the Mediterranean Sea was lower during the last glaciation period (Berné et al., 1999; Lofi et al., 2003).

The high density of *C. verticillata* in the Bourcart canyon is unusual in the Mediterranean Sea and has never been reported before. Many colonies of *C. verticillata* were entangled in bottom lines and fishing nets. This led us to assume that the high diversity sheltered by the structure-forming gorgonians is attractive for local fisheries even if the area is located far from the coast (60 km). In the French canyons their recorded living depth, generally located around 350 m, is targeted by bottom line fisheries.

From all these observations we propose that the fragile and poorly known *C. verticillata* should be considered as a sensitive species deserving interest and protection. These *C. verticillata* colonies have also been reported to be damaged by fishing activities on the continental shelf in the Tyrrhenian Sea (Bo et al., 2012).

4.2.4 Cold-water coral distribution

The CWC populations in both the Lacaze-Duthiers and Cassidaigne canyons were visited during the cruises described in this study. As previously known (Reyss, 1970; Zibrowius, 2003) the two scleractinian species *Lophelia pertusa* and *Madrepora oculata* were present in the Lacaze-Duthiers canyon (with *M. oculata* dominating over *L. pertusa*) while the single species *M. oculata* was present in the Cassidaigne canyon.

In the Lacaze-Duthiers canyon, the largest colonies (> 50 cm) of *L. pertusa* were observed along its western flank at two deep locations (350 m and 541 m depth), whereas colonies of *M. oculata* were located on both flanks at shallower depths (246 to 531 m on the west flank; 260 m on the east flank). The difference between the bathymetrical distribution pattern of *L. pertusa* and *M. oculata* could be explained by the lower tolerance of *L. pertusa* to temperature variations, since it is known that they are exposed to their maximal thermal limit in the Mediterranean Sea (Gori et al., 2013). To explain the preferential distribution of the *L. pertusa* and *M. oculata* colonies on the west flank we can assume that both flanks of the Lacaze-Duthiers canyon have different erosion regimes due to strong dense shelf water cascading on this side of the Gulf of Lion, which is similar to what happens in the Cap de Creus canyon (the next canyon westwards in Spanish waters). The bathymetric map (Fig. 7A) clearly shows that the east flank of the canyon exhibits a smooth morphology whereas the west flank exhibits steep slopes, probably due to an erosive regime (Orejas et al., 2009; Palanques et al., 2006). The erosive regime results in three favourable conditions for CWC settlement: (1) a periodic nutritive supply; (2) periodic washing of the sediment cover, leaving rocky outcrops available for settlement; (3) a rapid drop in temperature at depth (Puig et al., 2008). Colonies were oriented horizontally or downwards which is assumed to be a compromise between protection from the sediment flux and exposure to water flow to ensure feeding (Gori et al., 2013).

The Cassidaigne canyon is the other location for dense populations of scleractinian corals and sponges in the French Mediterranean Sea. The CWC community is exclusively located on the western flank of the canyon. Due to the prevailing westerly shelf currents, the eastern flank of the Cassidaigne canyon presents a prevalence of mud sediment draped over the bedrock, whereas the bedrock of the opposing western flank is much more exposed and characterised by spurs, terraced rock ledges, karstic dissolution features of former low sea-levels (e.g., the Messinian Salinity Crisis) and escarpments. The broad canyon head is fed by three tributary gullies and two spurs on both the eastern and western flanks form a bottleneck for the strong up- and downwelling hydrodynamic regime observed. On the western spur high diversity was observed with a combination of species from the shelf and from the CWC community. Mature *M. oculata* colonies grew mostly on the flanks of exposed bedrock. Small colonies of *M. oculata* were observed covering vertical walls at two locations at 360 m and around 450 m depth. They were considered as on-going and active settlement events in the Cassidaigne canyon.

We observed a high diversity of associated species in the Cassidaigne canyon. Deep occurrences of *Corallium rubrum* colonies were recorded living together with *M. oculata* colonies on the undersides of rock ledges or cave roofs from 200 to 325 m depth. This co-occurrence has been described recently in the Sicilian Channel at 458 m depth off Malta and at 673 m in the Linosa Trough (Costantini et al., 2010; Freiwald et al., 2009). Four species of Antipatharia (*Leiopathes glaberrima*, *Parantipathes larix*, *Antipathella subpinnata* and *Antipathes* cf. *dichotoma*) were also present in high abundance whereas they were not observed in the Lacaze-Duthiers canyon. This could be explained by the heavy load of suspended particles observed in the Lacaze-Duthiers canyon associated with a strong current that would be detrimental to the soft tissues of antipatharians (Wagner et al., 2012).

During the past decade, knowledge on live CWC communities in the Mediterranean Sea supported by *L. pertusa, M. oculata* and to a lesser degree by *Dendrophyllia cornigera* has increased considerably. Major coral hotspot areas are now known (Fink et al., 2013; Freiwald et al., 2009). The two CWC locations described in this paper are different from each other. The Lacaze-Duthiers CWC location is heavily loaded in particles and associated species are different from those in the Cassidaigne canyon. The latter is one of the shallowest locations (210 m depth) together with the Strait of Gibraltar (150 m depth, (Alvarez-Perez et al., 2005; De Mol et al., 2012) in which CWCs have been found. The Lacaze-Duthiers canyon is geographically close and similar in composition to the CWC community in the Cap de Creus canyon (Gori et al., 2013; Orejas et al., 2009).

The structure-forming CWC scleractinians of the Mediterranean Sea have been described to live mostly on vertical walls (this study, (Freiwald et al., 2009). They have also been described on vertical structures in the Atlantic canyons but to a greater extent, e.g., Whittard canyon, Bay of Biscay (Huvenne et al., 2011). In the Mediterranean Sea, CWC communities are never as large as those found in the Atlantic Ocean, where the prevailing conditions are more favourable with water temperatures around 4°C and salinities around 35, whereas the Mediterranean Sea is a relatively warm (up to 13.8°C) and salty basin (salinity as high as 39). According to current knowledge of the temperature limits for CWC, the Mediterranean Sea is close to the upper limit of many CWC occurring in the bathyal zone (25.5°C for *M. oculata* in the Indian Ocean and 14.7°C for *L. pertusa* in the Atlantic Ocean) (Keller and Os'kina, 2008).

4.2.4 Cold-water corals and lost fishing gears on rocky substrates

Lost fishing gears were observed in high densities together with CWC communities in both the Lacaze-Duthiers and Cassidaigne canyons. This evidence of severe pressure from fishing shows that these ecosystems therefore act as habitats for fishing resources as CWC communities are three dimensional frameworks harbouring high diversity and a rich trophic network.

Long lines and ropes entangling colonies of CWC were evidence of this fishing pressure, but these fishing gears represent only a percentage of the total effect of fishing on these CWC communities as we assume that fishing equipment is not frequently lost. Nevertheless these three-dimensional structures may be broken without any loss of equipment, as shown by the detached colonies laying on the seafloor. Moreover scleractinians and associated species may be by-catch for bottom long line fishing, therefore leaving no evidence (Sampaio et al., 2012).

In order to quantify the impact of fishing on hard substratum communities, account must be taken not only of lost fishing gears but also of detached colonies. However, the detached colonies may either be the result of the fishing pressure or due to their natural growth process. Indeed, the old basal parts were infested by fixo-sessile communities (sponges, polychaetes, *Neopycnodonte cochlear, Desmophyllum dianthus*) and excavated by bioeroding endobionts (Beuck et al., 2010), making them fragile and heavier, finally causing them to fall. We can also add another impact caused by scientific underwater vehicles which can encounter navigation difficulties in these complex environments, resulting in breaking these luxuriant and fragile colonies.

4.2.5 Cold-water coral and bauxite red mud disposal

The Cassidaigne canyon is considerably affected by the massive disposal of bauxite residues (Dauvin, 2010). These red residues are expelled by an aluminium company (operated successively by Pechiney, Alcan, Rio Tinto, Alteo) located 40 km inland at Gardanne (Bouches-du-Rhône, France). From 1967 to 1988, this red mud was discharged through two pipelines from two separate factories at 320 m depth near the canyon head. Since 1988, one of the factories stopped production and ceased using one of the pipelines, resulting in the reduction of the discharge of red mud. For more than 45 years, this mud has spread along the canyon, on the lateral flanks and down to the abyssal plain, contaminating the seabed with excess iron, titanium, vanadium and chromium (Fontanier et al., 2012).

Our visual inspection of the potential impact of the red mud on the benthic megafauna underpins a selective negative if not potentially lethal effect, as the megafauna diversity observed in 2009 was lower than that observed in 1971 (Bourcier and Zibrowius, 1973). Moreover colonies of gorgonians (*Acanthogorgia hirsuta*) were smothered with red mud and generally showed clear signs of tissue necrosis and patches of mud flocs. Frequently, basal portions of cnidarians were covered by red mud, although living parts were very clean, suggesting an effective mechanism against high sedimentation rates.

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. The episodically severe up- and downwelling current regimes may be the driving force for the complete spatial coverage of the natural seabed by man-made discharges. The burial of the rocky substrates suitable for the settlement of *Madrepora oculata* prevent them from expanding deeper than 350 m. The few *M. oculata* colonies observed deeper on blocks rising from the red mud bottom probably settled before the start of the disposal of the red mud. The highest abundances of *M. oculata* in the red mud environment were always observed on vertical walls where colonies were partly sheltered from silting. These colonies seemed to cope with the heavy sedimentation load but at a metabolic cost that remains to be investigated. However, it may point to a specific stress tolerance of *M. oculata*.

The recently settled colonies may be a positive result of the decrease in the red mud outflow since 1988. The objective to stop the outflow by 2015 would certainly help these protected species to survive.

4.3 Distribution of anthropogenic litter

The economic impact of tourism, fishing and coastal urban populations has been demonstrated to be important in the north western Mediterranean sea, where different types of debris were found on the deep sea floor (Galgani et al., 1996). It was shown that only small amounts of debris were collected on the continental shelf from the Gulf of Lion whereas most of the debris was found in deeper areas, mainly in zones with high sedimentation rates such as submarine canyons. In our MEDSEACAN study, higher concentrations of litter were observed in the Ligurian Sea than in the Gulf of Lion. This is linked to the narrow continental shelf in this area, with more coastal canyons. This is also related to the general circulation of the water flowing to the south in the Gulf of Lion as a consequence of both strong Northwest winds and the very considerable discharge of the Rhone River. The highest concentrations of metal objects observed in both the Toulon and Sicié canyons were explained by the presence of a large military harbour with discarded equipment on the adjacent sea floor, including weapons and ammunition. Plastics were found everywhere, with a percentage to total debris up to 100 in the Sète canyon, but in low abundance, within the same range as that described previously (Barnes et al., 2009; Galgani et al., 2000; Mordecai et al., 2011; Ramirez-Llodra et al., 2011). Pieces of glass, mainly beer bottles, were observed in the Ligurian Sea and linked to both pleasure boats and cruising ships. The Stoechades canyon contained quantities of wood debris coming from adjacent woods and forests from the three islands of Port-Cros, Porquerolles and Levant. Fishing-related objects were found in coastal canyons only, as a consequence of fishing activity. Finally, ceramics and other litter were spread everywhere but only in small quantities.

As mentioned previously (Galgani et al., 1996) debris in rocky environments cannot be evaluated by trawling. Video recording is therefore a valuable approach for evaluating litter which is often trapped in the rocky areas such as slopes. The mean concentration of litter calculated from submersible (Cyana) dives at the bottom of canyons were 24 items.km^{-1} (Galgani et al., 1996) on average, while the mean concentration measured on slopes in this study was 3 items.km^{-1}, which is far less. From both studies, it is clear that the amount of litter should not be considered as decreasing with time. We link this typical situation to several causes: (1) we explored the flanks of the canyons during the MEDSEACAN cruise on which the litter does not tend to accumulate; (2) the intensity of the light and the small area covered by the camera used with a small ROV such as Super Achille are respectively lower and narrower (1 meter in width) than with the manned submersible Cyana. The latter enabled surveying a strip 4-5 meters wide on soft bottoms. Overall, the analysis of results provides more detailed information on the diversity of debris typically related to coastal activities including fishing, harbours and tourism.

4.4 *Vulnerable Marine Ecosystems and their preservation*

Different international organisations (International Council for the Exploration of the Sea ICES, United Nations, European Commission, General Fisheries Commission for the Mediterranean GFCM) and Conventions (OSPAR, CITES and Barcelona convention) have recommended protection and management of a list of species and habitats that are either "sensitive", "vulnerable", "threatened" or "in decline", among which some are found in deep-sea ecosystems. All these conventions have led to the establishment of Marine Protected Areas (MPA) in all the world’s oceans. Three MPAs and one fishing area with restricted access have been created recently in the French part of the Mediterranean Sea (Fig. 14).

The "Parc Marin du Golfe du Lion" (decree 2011-1269) includes CWC communities of the Lacaze-Duthiers canyon and *Isidella elongata* communities of the Bourcart canyon. This park should implement new regulations to protect these areas against bottom fishing which is the most direct and the most noticeable threat to these ecosystems. Another specific site to be protected in this park is the rocky slab in the Bourcart canyon with high diversity associated with *Callogorgia verticillata* colonies.

The "Parc National des Calanques" (decree 2012-507) including the CWC communities of Cassidaigne canyon has defined several areas with specific regulations. Two of them are delimited on the western flank of Cassidaigne canyon: a "reinforced protection zone" and a "no-take zone". The "reinforced protection zone" is a "no-take zone" with some exceptions for local artisanal fishermen who were making their living there before the creation of the park. These two special zones have been defined to protect CWC communities from fishing. The "reinforced protection zone" allowing exceptional fishing is not located at the CWC location but at that where the disposal of red mud occurs. CWC communities are protected from fishing (long lines and nets) but not from the red mud discharged in this canyon which will cause long term disturbance even after the end of disposal.

Contamination of the trophic chain could occur in the future when red mud disposal will stop in 2015, causing a change in environmental conditions and possibly leading to the release of heavy metals into the environment (Fontanier et al., 2012). Contamination of the trophic chain in the Cassidaigne canyon by heavy metals could lead to sanitary consequences. Based on the precautionary principle we think fishing should be completely prohibited in Cassidaigne canyon. New studies will be launched to study this potential contamination by heavy metals.

The "Parc National de Port-Cros" (decree 2012-649) has been recently extended to include the adjacent bathyal seafloor, where we referenced no vulnerable ecosystems.

Additionally, the Scientific Advisory Committee of the GFCM has set up a fishing area with restricted access off the French coast in the Gulf of Lion, in which the fishing effort shall not exceed the level of fishing effort applied in 2008 (GFCM, 2009b). This area includes the Montpellier, Petit-Rhône and Grand-Rhône canyons and has been designated as a refuge from trawling for a non-exploited spawning fraction of the demersal fishing stock (Farrugio, 2012). However, this area has not been designated for the protection of sensitive ecosystems, despite the fact that the fishing effort has been limited to present levels since 2008. Nonetheless the benthic ecosystems may have been damaged already.

Vessel Monitoring System (VMS) data could be used in order to highlight areas of heavy fishing pressure. Afterwards, the data collected from these areas should be crossed with VME spatial distribution data to set up specific conservative measures.

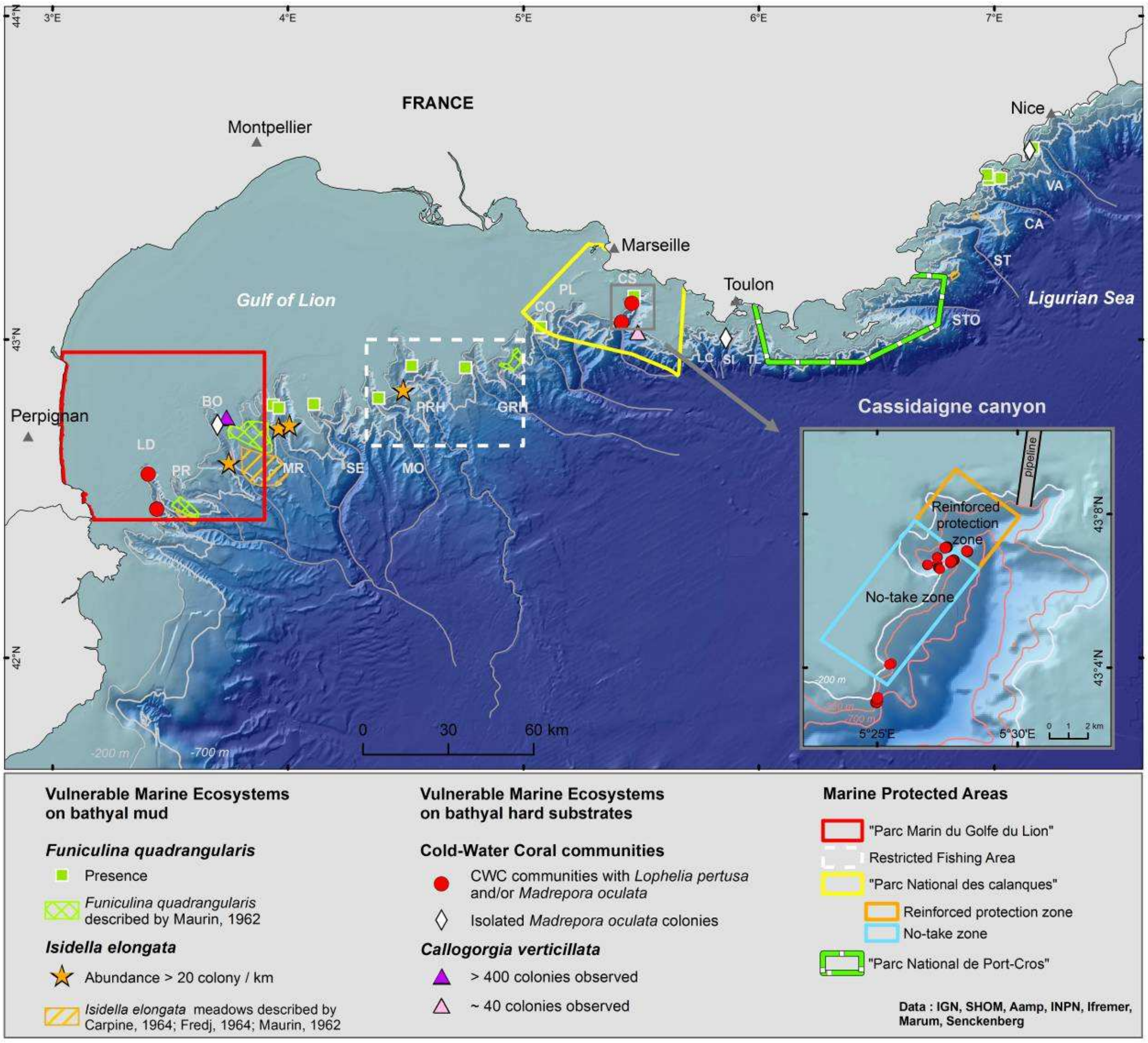

Fig. 14. *Geographical localisation of the Vulnerable Marine Ecosystems and the Marine Protected Areas of the French continental coast of the Mediterranean Sea. Submarine canyons from West to East: LD: Lacaze-Duthiers, PR: Pruvost, BO: Bourcart (Aude), MR: Marti (Hérault), SE: Sète, MO: Montpellier, 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.*

5. Conclusions

Video data were used to carry out an inventory of the distributions of benthic communities in the heads of French canyons considered to be vulnerable to anthropogenic impacts. This study is the first to have enabled: (1) the comparison of 17 canyons sampled in the same bathymetrical range over a limited temporal timescale (1 year), and (2) the observation of the soft substrate of Vulnerable Marine Ecosystems (VME) in situ instead of sampling by trawling or coring.

The Canyons of the Gulf of Lion are different from those of the Ligurian Sea with regard to their abundance in resources, VME fauna, substrates and anthropogenic impacts. Soft bottom VME fauna (Isidella elongata and Funiculina quadrangularis), resources and trawling impacts were mainly located in the Gulf of Lion. These VME fauna seem to have been swept away by repeated trawling. Access to Vessel Monitoring System data could help to better evaluate fishing impacts on these communities.

Cold-water coral communities (Lophelia pertusa, Madrepora oculata) are present in two of the French canyons (Lacaze-Duthiers and Cassidaigne). Fishing and silting (e.g. red mud) are the major impacts affecting these ecosystems presenting high diversity. We propose that the community of the gorgonian Callogorgia verticillata should be considered a VME taxa as it was rarely observed, it has been severely impacted and is associated with a high species diversity.

All these VME fauna are located in the recently created Marine Protected Areas where new regulations including deep-sea ecosystem conservative measures must be drafted.

This initial assessment of VME distribution was performed using historical and recent available data. New data must be collected for the future assessment of the ecological status of benthic ecosystems to be carried out as part of the Marine Strategy Framework Directive.

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Table 1

List of MEDSEACAN 2009 dives ordered by canyon. For each dive the latitude/longitude of the dive's gravity centre, the length of the navigation track, the depth (min, max, mean), the distance to the coast, the mean slope and the percentage of hard/soft substrate are mentioned. Canyons are listed from westward to eastward.

Canyon	Explored length (km)	Dive nb	Latitude	Longitude	Length (m)	Min Depth(m)	Max Depth (m)	Mean Depth (m)	Distance (degrees)	Mean slope (degree)	Hard substrate (%)	Soft substrate (%)
		P2	42°33.294 N	3°24.090 E	606	240	256	248	0.2445	27	100	0
		P3	42°35.010 N	3°24.258 E	1553	200	310	255	0.2669	19	50	50
		P6	42°32.598 N	3°25.056 E	1752	200	542	371	0.2398	24	20	80
Lacaze-Duthiers	10.97	P7	42°32.934 N	3°26.316 E	1490	183	550	367	0.2541	26	0	100
		P11	42°35.028 N	3°23.280 E	990	183	280	232	0.2535	19	50	50
		P13	42°31.152 N	3°26.388 E	2853	201	665	433	0.2292	22	0	100
		P14	42°34.794 N	3°24.336 E	595	203	360	282	0.2665	19	50	50
		P15	42°33.816 N	3°23.862 E	1131	321	385	226	0.2516	33	80	20
		P1	42°30.618 N	3°32.646 E	1489	202	523	363	0.2924	20	0	100
Pruvost	3.84	P2	42°31.980 N	3°32.928 E	1035	200	475	338	0.3100	21	0	100
		P5	42°32.454 N	3°30.444 E	316	180	235	208	0.2877	14	0	100
		P6	42°33.360 N	3°31.560 E	996	194	368	281	0.3116	17	0	100
		P2	42°43.248 N	3°40.860 E	1359	203	463	333	0.5379	19	0	100
Bourcart	6.16	P5	42°36.792 N	3°45.114 E	1584	377	625	501	0.5203	24	0	100
		P6	42°43.476 N	3°44.778 E	1669	253	403	328	0.5857	12	0	100
		BO_R2K	42°44.670 N	3°43.050 E	1549	310	360	335	0.5605	15	90	100
		P1	42°43.326 N	3°57.660 E	1988	374	609	492	0.7081	24	0	100
Marti	5.38	P2	42°47.538 N	3°55.980 E	1348	190	378	284	0.6357	15	0	100
		P4	42°47.184 N	3°57.816 E	672	226	347	287	0.6611	22	0	100
		P5	42°43.926 N	4°0.282 E	1367	329	605	467	0.7264	21	0	100
		P1	42°41.976 N	4°9.606 E	1320	279	626	453	0.7610	20	0	100
Sète	4.73	P2	42°45.696 N	4°7.932 E	1214	315	540	428	0.7026	23	0	100
		P3	42°44.718 N	4°11.298 E	1856	231	700	466	0.7151	21	0	100
		P8	42°47.892 N	4°6.534 E	338	180	235	208	0.6701	4	0	100
		P1	42°48.906 N	4°22.548 E	3495	200	700	450	0.5817	20	0	100
Montpellier	8.96	P2	42°47.640 N	4°24.504 E	1550	185	613	399	0.5901	26	0	100
		P3	42°45.456 N	4°23.472 E	2038	260	600	430	0.6293	22	0	100
		P4	42°49.134 N	4°26.874 E	1881	200	402	301	0.5555	10	0	100
		P1	42°58.038 N	4°29.010 E	1899	343	408	376	0.4033	4	0	100
Petit-Rhône	9.24	P3	42°55.212 N	4°30.780 E	2367	180	487	334	0.4413	27	0	100
		P4	42°51.882 N	4°39.930 E	1891	268	600	434	0.4800	16	0	100
		P5	42°50.316 N	4°29.340 E	3084	206	627	417	0.5265	14	0	100
Grand-Rhône	5.83	P1	42°54.738 N	4°45.336 E	1794	180	420	300	0.4232	13	0	100
		P2	42°55.116 N	4°50.232 E	1669	190	427	309	0.4100	17	0	100
		P3	42°58.134 N	4°47.778 E	2366	410	443	427	0.3620	15	0	100
		P1	43°2.250 N	5°1.518 E	1804	202	571	387	0.2870	17	0	100
		P2	43°3.330 N	5°6.918 E	1896	200	500	350	0.2600	14	0	100
Couronne	10.40	P3	43°3.960 N	5°8.256 E	1299	203	501	352	0.2365	18	0	100
		P4	43°0.354 N	5°1.242 E	1962	209	551	380	0.3194	18	0	100
		P5	43°1.890 N	5°4.302 E	2118	275	550	413	0.2924	13	0	100
		P6	43°0.618 N	5°7.848 E	1324	325	542	434	0.2800	18	0	100
Planier	17.90	P1	43°6.108 N	5°12.372 E	1033	213	420	317	0.1613	20	60	40

		P2	43°5.316 N	5°12.540 E	728	338	554	446	0.1683	32	90	10
		P3	43°4.386 N	5°13.194 E	983	309	640	475	0.1737	29	50	50
		P4	43°3.882 N	5°8.400 E	2553	180	585	383	0.2361	19	0	100
		P5	43°5.982 N	5°13.938 E	528	418	486	452	0.1445	11	0	100
		P6	43°7.188 N	5°12.684 E	1517	180	313	247	0.1449	13	10	90
		P7	43°6.432 N	5°12.456 E	3954	200	452	326	0.1571	18	70	20
		P8	43°6.552 N	5°14.526 E	675	340	390	365	0.1319	11	60	40
		P9	43°4.944 N	5°11.670 E	1884	200	593	397	0.1838	21	10	90
		P10	43°5.376 N	5°14.082 E	1868	232	425	329	0.1509	12	0	100
		P11	43°6.732 N	5°14.514 E	859	195	340	268	0.1289	14	50	50
		P12	43°5.718 N	5°12.642 E	498	225	439	332	0.1641	34	90	10
		P13	43°5.496 N	5°12.564 E	824	266	413	340	0.1655	34	90	10
Cassidaigne	8.12	P1	43°6.756 N	5°27.630 E	2179	205	215	210	0.0863	19	100	0
		P2	43°2.598 N	5°24.048 E	1327	448	634	541	0.1282	41	100	0
		P3	43°2.808 N	5°23.850 E	1210	285	470	378	0.1241	27	80	20
		P4	43°5.364 N	5°25.752 E	767	180	386	283	0.0899	29	70	30
		P6	43°8.028 N	5°28.158 E	855	210	465	338	0.0672	22	20	80
		P7	43°1.272 N	5°29.184 E	900	200	470	335	0.1729	36	60	40
		P8	43°3.636 N	5°29.400 E	879	214	508	361	0.1361	33	60	40
La Ciotat	7.25	P1	43°1.404 N	5°43.254 E	2091	180	600	390	0.0738	30	80	20
		P2	43°0.498 N	5°40.848 E	1350	180	498	339	0.1122	20	80	20
		P3	42°58.746 N	5°42.024 E	2492	216	583	400	0.1206	19	20	80
		P5	42°57.780 N	5°38.028 E	1318	180	518	349	0.1771	24	40	60
Sicié	8.70	P1	43°0.846 N	5°52.542 E	1449	180	398	289	0.0358	22	40	60
		P2	42°59.538 N	5°54.630 E	1446	180	486	333	0.0736	32	30	70
		P4	43°0.972 N	5°53.604 E	1516	180	580	380	0.0453	32	40	60
		P5	42°59.958 N	5°51.612 E	2460	180	560	370	0.0480	27	10	90
		P7	43°0.936 N	5°52.434 E	529	180	280	230	0.0331	20	50	50
		P8	43°0.660 N	5°55.038 E	1296	185	420	303	0.0560	31	70	30
Toulon	7.75	P4	43°24.048 N	6°55.212 E	2021	180	731	456	0.0382	24	30	70
		P5	43°2.346 N	5°58.158 E	1502	180	547	364	0.0369	20	40	60
		P6	42°58.416 N	5°57.000 E	2033	190	687	439	0.0921	22	90	10
		P7	43°1.932 N	6°0.198 E	2192	180	593	387	0.0487	25	40	60
Open slope	17.69	PO_P1	42°56.838 N	6°16.866 E	651	402	645	524	0.0611	30	90	10
		PO_P5	42°57.624 N	6°19.938 E	1332	180	627	404	0.0533	40	40	60
		PO_P6	42°56.400 N	6°14.076 E	2285	202	418	310	0.0494	27	30	70
		PO_P8	42°56.646 N	6°6.426 E	3230	195	710	453	0.0764	28	20	80
		PO_P9	42°56.862 N	6°14.982 E	2244	200	705	453	0.0481	29	60	40
		PO_P10	42°56.280 N	6°7.914 E	1748	317	557	437	0.0671	17	30	70
		MG_P10	43°1.488 N	6°38.742 E	1332	250	598	424	0.1358	32	20	80
		MG_P11	42°57.840 N	6°21.234 E	1516	180	800	490	0.0367	36	60	40
		MG_P16	43°0.060 N	6°32.088 E	1804	224	548	386	0.0501	32	70	30
		MG_P17	43°0.210 N	6°29.766 E	1544	180	673	427	0.0268	35	70	30
Stoechades	7.39	MG_P3	43°4.362 N	6°31.674 E	1515	252	707	480	0.0283	32	40	60
		MG_P4	43°3.846 N	6°28.266 E	695	180	394	287	0.0161	20	0	100
		MG_P5	43°8.730 N	6°40.686 E	1283	180	722	451	0.0361	30	40	60
		MG_P6	43°8.058 N	6°33.738 E	1200	200	515	358	0.0397	21	0	100
		MG_P7	43°5.244 N	6°26.916 E	558	300	322	311	0.0465	6	0	100
		MG_P14	43°4.470 N	6°34.296 E	956	302	652	477	0.0662	34	10	90
		MG_P15	43°8.868 N	6°37.368 E	1180	200	524	362	0.0100	32	70	30

Cannes	11.15	P3	43°29.754 N	7°1.236 E	2905	180	692	436	0.0189	29	10	30
		P4	43°29.784 N	6°58.824 E	2440	180	537	359	0.0240	32	50	50
		P5	43°30.744 N	6°58.716 E	1680	200	484	342	0.0242	23	0	100
		P6	43°28.794 N	7°3.516 E	4128	180	631	406	0.0260	32	0	100
Var	15.47	P1	43°40.656 N	7°17.238 E	6332	180	700	440	0.0100	26	20	80
		P2	43°39.930 N	7°20.790 E	2279	180	355	268	0.0144	17	10	90
		P6	43°40.932 N	7°17.610 E	324	180	290	235	0.0028	38	100	0
		P10	43°35.748 N	7°10.434 E	2455	315	586	451	0.0428	24	40	60
		P11	43°35.898 N	7°9.918 E	4082	180	456	318	0.0354	29	20	80

Table 2

List of additional dives processed for qualitative information in the Lacaze-Duthiers and Cassidaigne canyons. For each dive the length of the navigation track, the latitude of the dive's gravity centre, the longitude of the dive's gravity centre and the depth (min, max, mean) are mentioned.

Canyon	Cruise	Dive nb	Latitude	Longitude	Length (m)	Min Depth(m)	Max Depth (m)	Mean Depth (m)
Lacaze-Duthiers	Marum Senckenberg 2011 Super Achille ROV	D1	42°33.553 N	3°25.540 E	847	250	450	350
		D2	42°33.677 N	3°23.945 E	35	300	350	325
		D3	42°33.675 N	3°23.953 E	1905	325	325	325
		D5	42°28.300 N	3°27.300 E	1905	200	600	400
		D6	42°33.100 N	3°24.460 E	494	250	450	350
		D7	42°33.110 N	3°24.451 E	249	250	400	375
Cassidaigne	Marum 2009 Super Achille ROV	D1	43°7.094 N	5°28.404 E	97	460	478	469
		D2	43°6.507 N	5°27.249 E	2745	184	240	212
		D3	43°3.170 N	5°28.602 E	963	516	564	540
		D4	43°3.280 N	5°29.905 E	1670	231	419	325
		D5	43°6.603 N	5°26.756 E	1561	198	370	284
		D6	43°6.810 N	5°25.930 E	1070	134	280	207
		D7	43°6.712 N	5°27.153 E	2101	243	465	354
		D8	43°6.583 N	5°27.227 E	307	187	237	212
		D9	43° 4.102 N	5°25.519 E	1289	246	454	350
	Marum 2009 Remora submersible	R1	43° 6.977 N	5° 28.120 E	3851	320	530	425
		R2	43° 3.103 N	5° 24.978 E	5557	250	500	375
		R3	43° 7.060 N	5° 30.321 E	3774	230	530	380
		R4	43° 6.834 N	5° 27.925 E	2323	280	400	340
	Ifremer Cyatox 1995 Cyana Submersible	1214-03	43°7.000 N	5° 27.000 E	6276	292	646	469
	Ifremer ESSROV 2010 Victor 6000 ROV	397-01	43° 7.009 N	5° 28.162 E	998	251	400	326
		401-05	43° 6.473 N	5° 27.284 E	4248	60	284	172
		407-11	43° 7.206 N	5° 28.846 E	3216	601	750	676

Table 3

List of fishes observed during MEDSEACAN 2009 cruise classified in three categories: Marketable (M), Edible (E) and Others (O). The total abundance and maximum depth at which they were observed is mentioned. (M*) *Trachurus* sp. is a pelagic marketable species that has been removed from the following of the study.

Class Order	Family	Genus species	Total effectif observed	Maximum Depth (m)	M	E	O	English name	French name
Actinopterygii									
Anguilliformes		sp. gen.	1	442			O		
	Congridae	*Conger conger*	23	555		E		Conger	Congre
Aulopiformes	Chlorophthalmidae	*Chlorophthalmus agassizi*	8	464			O		
	Synodontidae	*Synodus saurus*	1	330			O		
Beryciformes	Trachichthyidae	*Hoplostethus mediterraneus*	29	599			O		
Gadiformes	Gadidae	*Gadiculus argenteus*	127	504			O		
		Lepidion lepidion	1	686		E		Mediteranean codling	Morue Mediterranéenne
		Micromesistius poutassou	16	655	M			Poutassou / blue whiting	Merlan bleu
	Lotidae	*Molva macrophthalma*	6	448		E		Spanish ling	Lingue espagnole
	Macrouridae	sp. gen.	28	709			O		
		Coelorinchus caelorhincus	192	579			O		
		Hymenocephalus italicus	15	617			O		
		Nezumia aequalis	16	708			O		
		Trachyrincus scabrus	23	696			O		
	Merluciidae	*Merluccius merluccius*	57	645	M			Hake	Merlu / Colin
	Moridae	sp. gen.	5	618			O		
	Phycidae	*Phycis blennoides*	140	689		E		Greater forkbeard	Mostelle blanche de vase
		Phycis phycis	2	360		E		Forkbeard	Mostelle brune de roche
		Phycis sp.	4	320		E		Forkbeard	Mostelles
Lophiiformes	Lophiidae	*Lophius piscatorius*	8	456	M			Monkfish	Lotte / Baudroie
Myctophiformes	Myctophidae	sp. gen.	21	670			O		
Notacanthiformes	Notacanthidae	*Notacanthus bonaparte*	7	619			O		
Ophidiiformes		sp. gen.	4	473			O		
	Carapidae	*Echiodon dentatus*	1	431			O		
	Ophidiidae	*Benthocometes robustus*	5	634			O		
Osmeriformes	Argentinidae	*Argentina sphyraena*	57	408			O		
Perciformes	Callionymidae	*Synchiropus phaeton*	2	347			O		
	Caproidae	*Capros aper*	126	431			O		
	Carangidae	*Trachurus* sp.	shoals	488	M*			Horse mackerel	Chinchard
	Epigonidae	*Epigonus denticulatus*	5	491			O		
		Epigonus telescopus	2	423			O		
	Labridae	*Acantholabrus palloni*	35	381			O		
	Mullidae	*Mullus barbatus*	1	208		E		Red mullet	Rouget barbet (de vase)
		Mullus sp.	3	320		E			
	Polyprionidae	*Polyprion americanus*	3	627	M			Wreckfish	Cernier
	Serranidae	*Anthias anthias*	shoals	239			O		
	Sparidae	sp. gen.	1	250			O		
		Pagellus sp.	13	403	M			Sea-bream	Pageot
	Trichiuridae	sp. gen.	45	545	M			Cutlassfishes	Sabres
Pleuronectiformes	Scophthalmidae	*Lepidorhombus boscii*	56	580		E		Four spotted megrim	Cardine à 4 tâches
		Lepidorhombus whiffiagonis	5	302		E		Megrim	Cardine franche
Scorpaeniformes	Peristediifae	*Peristedion cataphractum*	4	342			O		
	Scorpaenidae	*Scorpaena scrofa*	50	465	M			Red scorpionfish	Rascasse rouge
	Sebastidae	*Helicolenus dactylopterus*	482	614		E		Blackbelly rosefish	Sebaste chèvre
	Triglidae	sp. gen.	22	476	M			Gurnards	Grondins

		Trigla lyra	77	488	M			Piper gurnard	Grondin lyre
Stomiiformes	Stomiidae	sp. gen.	1	705			O		
		Chauliodus sloani	3	593			O		
		Stomias boa	2	578			O		
Syngnathiformes	Centriscidae	*Macroramphosus scolopax*	3	262			O		
Zeiformes	Zeidae	*Zeus faber*	1	243	M				
Elasmobranchii		sp. gen.	11	690			O		
Carcharhiniformes	Scyliorhinidae	*Scyliorhinus canicula*	35	394	M			Lesser spotted dogfish	Petite roussette / saumonette
		Scyliorhinus sp.	3	379	M				Roussettes
	Triakidae	*Galeus melastomus*	91	505		E		Black-mouthed dogfish	Chien espagnol
Hexanchiformes	Hexanchidae	*Hexanchus griseus*	1	366			O		
Rajiformes	Rajidae	*Raja* sp.	1	478			O		
Squaliformes	Dalatiidae	sp. gen.	4	481			O		
		Etmopterus spinax	27	587			O		
		Oxynotus centrina	1	225			O		
Holocephali									
Chimaeriformes	Chimaeridae	*Chimaera monstrosa*	28	584			O		