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Regional Activity Centre For Specially Protected Areas

SICILY CHANNEL/TUNISIAN PLATEAU: TOPOGRAPHY, CIRCULATION AND THEIR EFFECTS ON BIOLOGICAL COMPONENT

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Contents

Abstract

This Sicilian Channel has complex bottom morphology. Two sill systems are separated by deep basins or grabens, the Eastern Sill system (Malta plateau and Medina Bank) connects the Sicilian Channel with the Ionian Basin. The Western Sill (Skerki bank, Adventure Bank, Empedocle seamount and the Nameless Bank) is the major obstacle to the Modified Mediterranean Water (MAW). Three major depressions, the Pantelleria graben (1317-m depth), Linosa graben (1529-m depth), and Malta graben (1731-m depth) are located on the middle of the channel. A large shallow shelf characterizes the area on the south close to the Tunisia and Libya. The Sicilian Channel is a high-energy site with a dynamic and highly variable current system that exchanges the waters between western and eastern basins. Three water masses characterize the circulation in the Sicilian Channel, the upper layer (about 200m thick) of MAW) flows eastward, the Levantine Intermediate Water (LIW) and the deeper layer of the Eastern Mediterranean Deep Water, which flow from the east toward the Tyrrhenian Sea and then to the Western Mediterranean. After entered onto the Sicily channel the MAW splits into two main branches Atlantic Ionian Stream (AIS) and Atlantic Tunisia Current (ATC). The complex circulation patterns together with bottom structures such as seamounts, banks, volcanoes, pockmarks and steep walled basins are the main responsible of the biodiversity richness of the Sicily Channel, where healthy deep coral communities find favourable habitat and several pelagic species such as anchovies, bluefin tuna and fin whales have spawning and feeding areas.

As subject of other reviews, here the physical effects on benthic commercial target species and pelagic such as sharks, swordfish and other cetacean species have not taken into account.

1 The Sicily Channel - Tunisia Plateau

1.1 Geographic limits of the Sicily Channel- Tunisia Plateau (Central Mediterranean)

The Sicily Channel has no universally accepted definition as well as shared names (i.e. Sicilian Channel, Sicilian Strait, Sicilian Narrow), it cover a great part of the Central Mediterranean being bounded by the Sicily island to the north, by the Tunisia-Sardinia Channel to the west, by Tunisia coasts to the south-west, Libyan coast to the south and Ionian sea to the east. Thus it corresponds to the westernmost part of the subarea 2.2 of the FAO area 37. The very complex topography and circulation patterns of the Sicily Channel make it a highly productive area and a biodiversity hotspot, moreover it play a fundamental role connecting the eastern and western Mediterranean sub-basins.

As the ecosystem features of the area largely depend from the physical and biological processes of the neighbouring regions, namely Tunisia-Sardinia Channel and Ionian sea, in this review the term Sicily Channel-Tunisia Plateau (hereafter Sicily Channel or Sicilian Channel) has been arbitrarily used to indicate the wide area bounded by shallow bottom features on the west, defined by the general term Western Sill (mainly Skerki bank, Adventure bank and related banks) and, on the east, by the steep slope of Medina-Malta Escarpment, by the Medina bank (Eastern Sill) and, from there to Misratah Cape by the 1000 m bathymetry (Fig. 1).

The Sicily strait (or strait of Sicily) has been use in order to indicate the Western Sill area and, in particular the narrow passage (about 90 nm wide) between Cape Bon (Tunisia mainland) and Cape Lilibeo (or Cape Boeo, near Marsala, Sicily island).
The Sicily Channel encompasses other features, which have been quoted in this review such as Pantelleria, Lampedusa, Linosa islands (Italy) and Kerkennah, Djerba islands (Tunisia), Gela basin, the Maltese archipelago, the Malta plateau (or Hyblean plateau), the Malta Channel, the Misratah valley (canyon), and on the Tunisia shelf, the Gulf of Hammamet and the Gulf of Gabes (Fig. 1).

Three main rift structures characterize the central area of the Sicily Channel, Pantelleria, Malta and Linosa grabens (basins, trough) as elongated depressions with NW-SE trending axes. These basins split into secondary grabens such as Malta-Medina and Medina-Melita grabens separating respectively the Maltese plateau from the Medina bank and Medina bank from the Melita bank (Fig. 1).

Many of the known as well as some unnamed (but rising more than 100m from the sea bottom) topographic structures such as seamounts, underwater volcanoes, banks, shoals, hills, patches, rises, etc. have also allocated according the EMODnet bathymetry map using 10m depth interval at 450 m horizontal grid (Tab. 1; Tab. 2; Fig. 2).

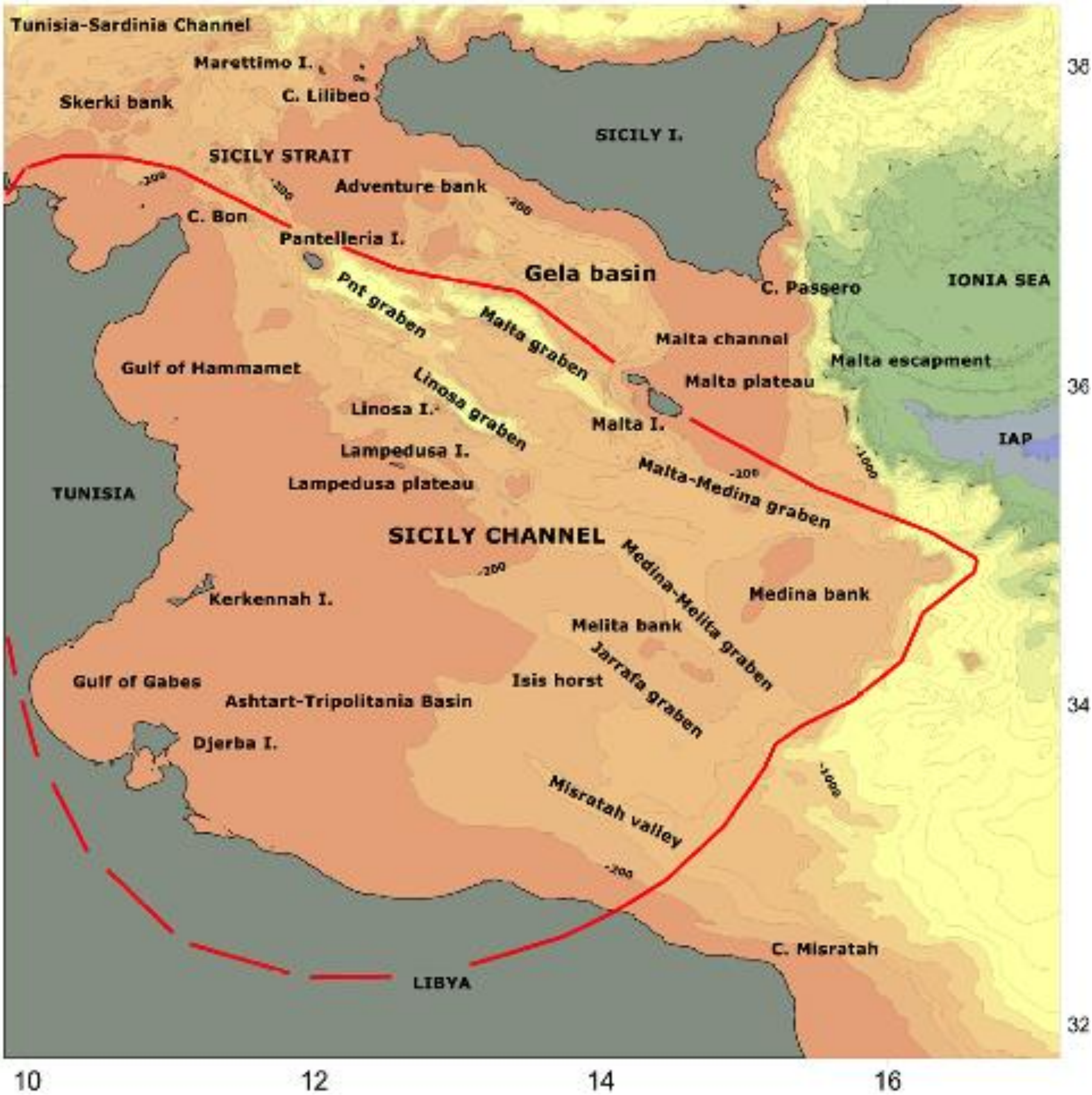

Fig. 1: The Sicily Channel-Tunisia Plateau main features as described in the text. The red line bounds the so-called Pelagian Province (Klett, 2001); IAP: Ionian Abyssal Plain.

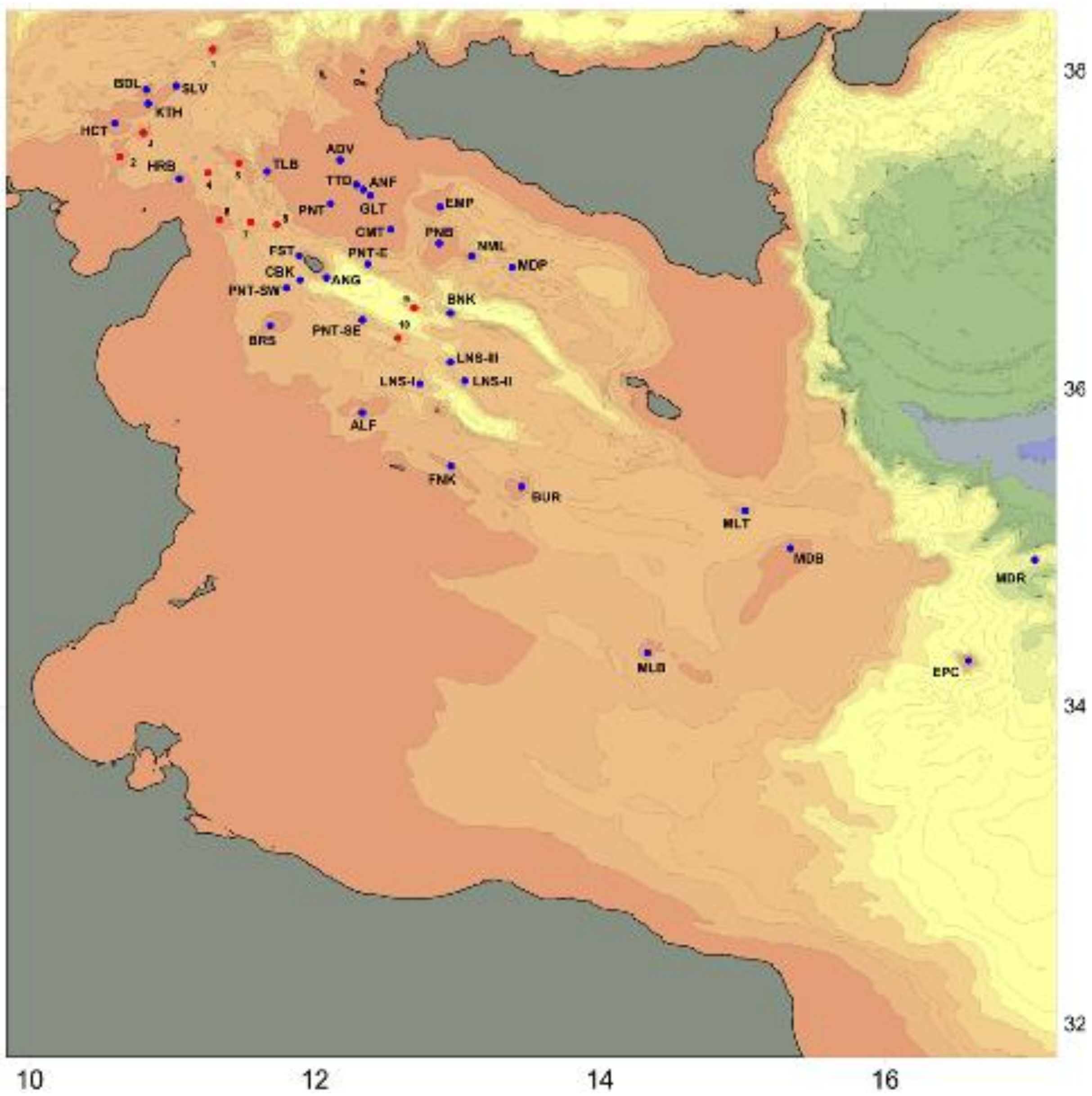

Fig. 2: Position of the seamounts, banks, submarine volcanoes and other rising structures in the Sicily Channel. The blue dots indicate the shallower bathymetry of those structures of which it was possible to find the name from scientific literature or other sources; red dots indicate the positions of unnamed structures. For both, the geographic coordinates have been estimated on the basis of the EMODnet bathymetry map, with 10 m depth interval at 450 m horizontal grid. For the code – name correspondence see Tab. 1 and Tab. 2. Depth contours every 200 m.

2 Topography and Bathymetry

The Sicily Channel is an area where the moving water strongly interacts with the ocean floor, thus topography and bathymetry both influence the flow of water and has direct implications on the bottom substrate characteristics, on aquatic habitats and distribution of fish populations.

The Sicily Channel connects the western and eastern Mediterranean sub-basins and is characterised by a complex bathymetry with wide continental shelves, deep and shallow channels as well as wide abyssal plains. It plays a crucial role in the passage of the superficial and intermediate water masses in transit between the eastern and the western Mediterranean sub-basins and also prevents the direct mixing of the water masses from the deep and bottom layers of the two sub-basins.

The complex topography and bathymetry of the Sicilian Channel is the result tectonic and magmatic processes, which mark the offshore continuation of the accretionary prism of Sicily (Corti *et al.*, 2006), where a NW-trending rift system crosscuts the Apennines-Maghrebides belt.

Carminati *et al.* (2010) summarize the processes as:

1. Pliocene–Pleistocene NW-dipping foreland monocline generating the overlying foredeep (Mariotti and Doglioni, 2000);
2. Roughly ENE-WSW to E-W-trending thin-skinned imbricate wedge, progressively emplaced from the Early-Middle Miocene to Present (e.g., Roure *et al.*, 1990a; Catalano *et al.*, 1996);
3. NW-trending normal faults and related grabens or half grabens, associated with a Pliocene-Recent rifting phase that led to the development of the Sicily Channel.

Toward the northwest, the Sicily Channel rift seems to be connected with the Campidano graben, in southwest Sardinia, and affects also the Pelagian shelf, onshore Tunisia and it continues to the southeast into the Sirte basin in Libya (Corti *et al.*, 2006).

This Sicilian Channel comprises two sill systems separated by an internal deep basin. The Eastern Sill system is divided in the Malta plateau and Medina-Melita banks and it has maximum depth of about 540 m and connects the Sicilian Channel with the Ionian Basin. The Western Sill is divided in several banks among which the larger is the Adventure bank.
Narrow shelf separates these large sill systems in the central part; here the shape of the slope is extremely irregular, incised by many canyons, trenches and steep slopes.

The eastern sill system is characterized by some extensive, shallow, generally flat-topped or

tabular, platforms. The topography of the continental shelf in this area is characterised by a plateau in the middle part, with an average depth of 150 m (Malta plateau). The shelf is flanked by a submarine ridge, which protrudes as a submerged extension of Cape Passero and embraces the shelf area along the eastern and southern perimeter. The Maltese Islands represent the emerged part of this ridge while Hurd bank to the north east of Malta shallows to a depth of just over 50 m.
Of particular interest is the Medina bank, southeast of Malta. This elongate topographic high serves as important barriers to water masses flowing across the platform.

The Medina uplift is characterized by a broad, convex-up topography (probably gentle anticlinal-like folds) and small distinct valleys. Faulting is not as prominent a feature in this zone as in the other outer margin environments of the Channel. The reduced sediment cover on the convex-up topography suggests a slow, uniform rate of sediment accumulation, or erosion by bottom currents or both (Maldonado and Stanley, 1976).

The positive Medina bank feature is bisected by a local graben, along the north side of which is the poorly defined ridge of the West Medina bank (Bishop and Debono, 1996). On its eastern extremity, it deepens abruptly into the deep Ionian sea with a very sharp escarpment (Malta Escarpment) and, likely, it continues into the Medina-Malta ridge, protruding into the Ionian Abyssal Plain as sub-bottom tectonic structure (Medina - Victor Hansen structure).

The strait between Cape Bon (Tunisia) and Cape Lilibeo (Sicily) is the narrowest constriction (1243km wide) and constitutes the main exchange passageway for the superficial and intermediate water masses between the two sub-basins. The flow is further limited by the highly irregular bottom topography of the western sill, which is bounded by a system of shallow (less than 50 m) banks: Skerki and Adventure banks, Empedocle seamount and Pinne-Nameless bank.

Skerki bank is a broad underwater ridge, which is about sixty miles from the island of Marettimo, essentially in the middle of the Strait of Sicily, between Sicily and Tunisia. In general, it consists of four ascents, each with a different name: on SW is the Hacate patch, which extends for about 3 miles in a succession of ridges and canyons and vast expanses of submerged boulders; follows, in the middle, the Keith reef, also called “point zero” as it has a rock that reaches 0.30 m from the surface, extends for about 2 miles between 10 and 20 meters characterized by cliffs and boulders that follow one another to form ridges. To the north west of Keith rises from the bottom the Biddlecombe plateau, less jagged then other rises but with gradients of more than 15 meters that fall into the deep. On the north east, closer to the Sicily, is the Silvia knoll, an extended plateau of white rock; over the plateau, when the depths go deeper, there are a series of long ridges, up to 1 mile long, with peaks between 18 and 24 meters (Fig. 3).

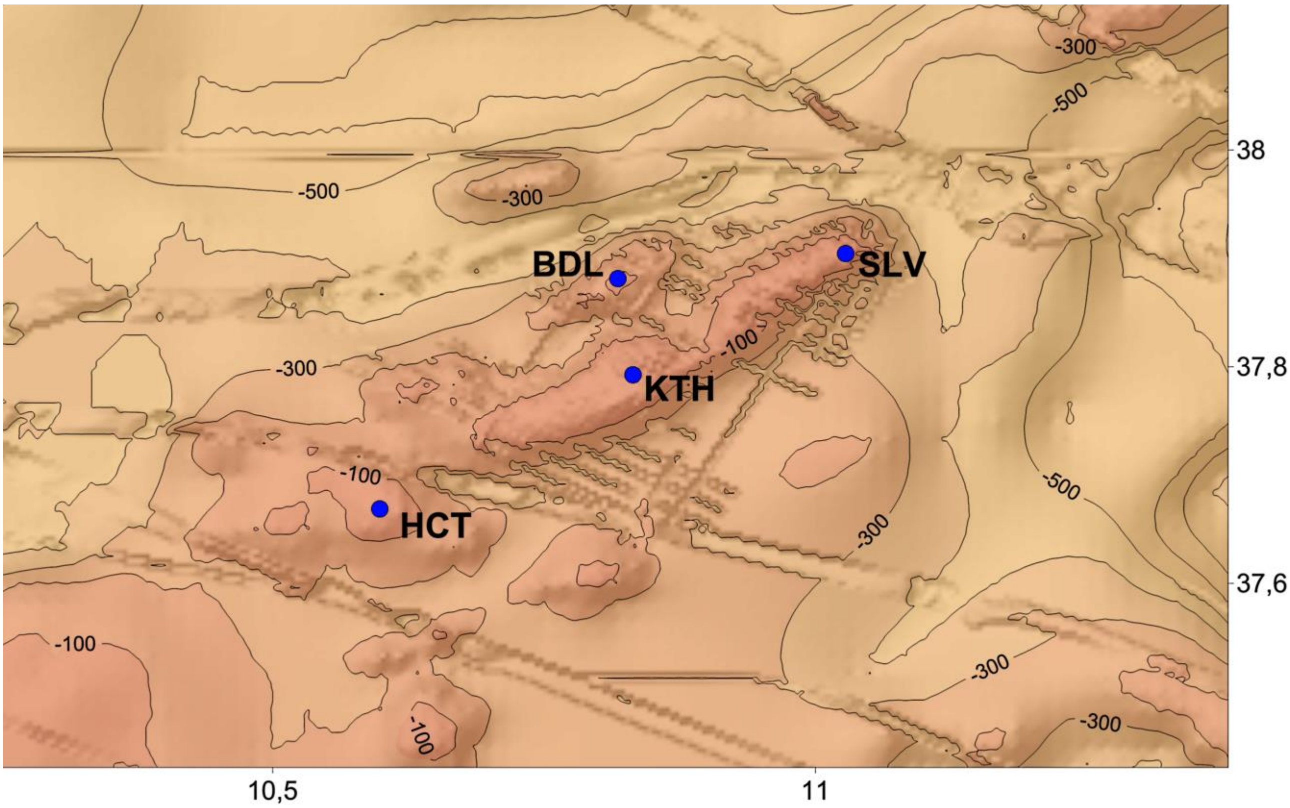

Fig. 3: Map of the Skerki bank, depth contours every 100 m. HCT, Hecate patch; KTH, Keith reef; BDL, Biddlecombe plateau; SLV, Silvia knoll.

The Adventure bank is the largest shallow platform in the Strait of Sicily (Fig. 4). The seismic profiles show that considerably reduced unconsolidated sediments, for the most part, cover this shallow platform. The unconsolidated strata are gently tilted, tectonically offset, and truncated. Adventure bank is essentially a horst structure consisting of Tertiary and Mesozoic deposits. Well-defined terraces are cut at about 110 m and at 140 m on some bank margins. The terrace at 140 m forms a gently dipping seaward slope, which may represent a foreshore surface.

A gentle slope, interrupted by small mounts and gentle depressions, characterizes most of the bank surfaces. This topography is largely the result of alternating erosion and deposition related to the Quaternary oscillations of sea level; recent structural activity, including diapirism and volcanism, also has affected this zone. In this respect, submarine mounts on the northern Adventure bank have been interpreted as diapiric structures and the southeast extension of this bank is interpreted as the most active volcanic area in the Strait. Minor submarine volcanic centres recognized in Adventure plateau (Anfitrite, Cimotoe, Galatea and Tetide) are also considered to be of Plio-Pleistocene age (Calanchi *et al.*, 1989; Rotolo *et al.*, 2006).

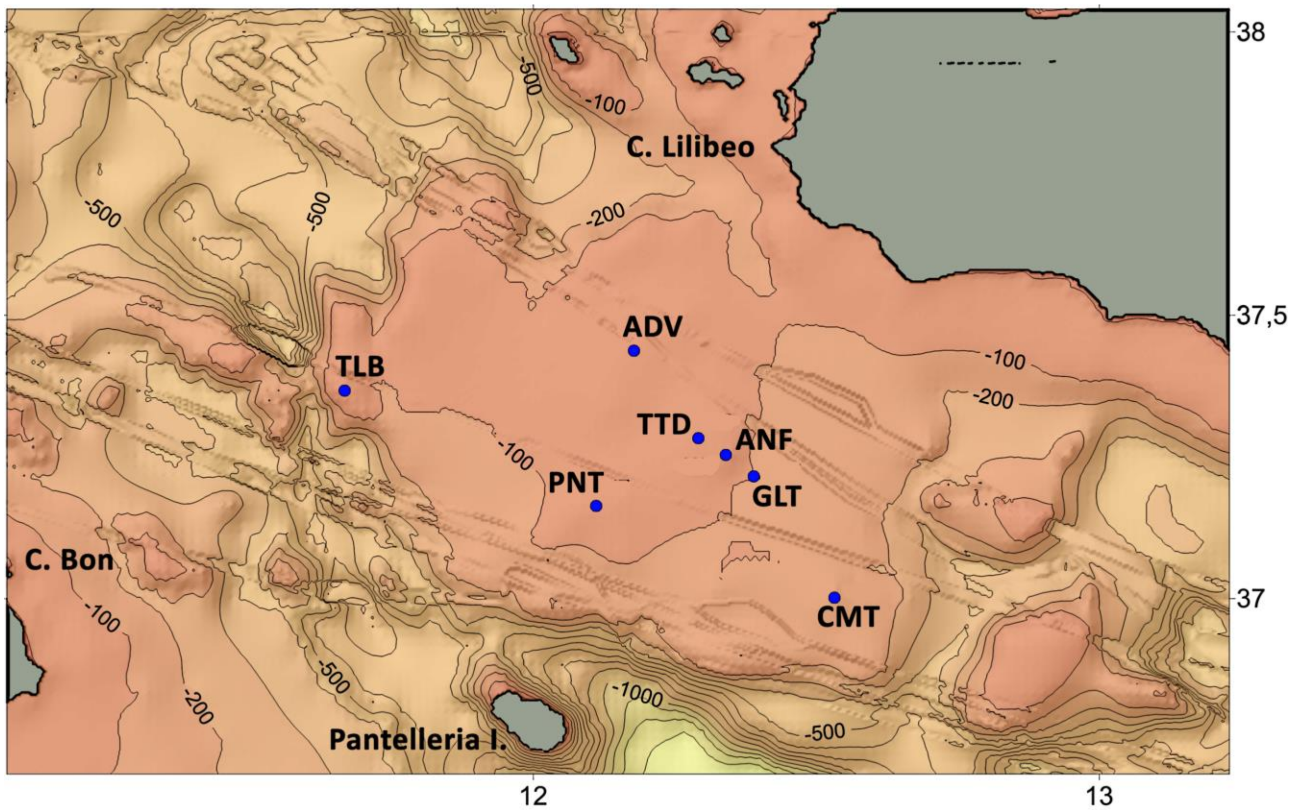

Fig. 4: Map of the Adventure bank, depth contours every 100 m. TLB, Talbot bank; ADV, Adventure bank; PNT, Pantelleria bank; TTD, Tetide volcano; ANF, Anfitrite volcano; GLT, Galatea volcano; CMT, Cimotoe, volcano.

The Empedocle seamount is a large underwater relief, rising on the deep sea floor from 250 m to about 500 m, on which are implanted dozen well-structured buildings of very variable dimensions, often aligned and lengthened according to the orientation of the Sicily Channel (NW-SE). Among them Graham bank (-6.9 m), which is on the building of Ferdinandea volcano, Nerita (-16.5 m) and Terrible (-20 m) banks, are arranged as an irregular horseshoe open to the NNW (Fig. 5).

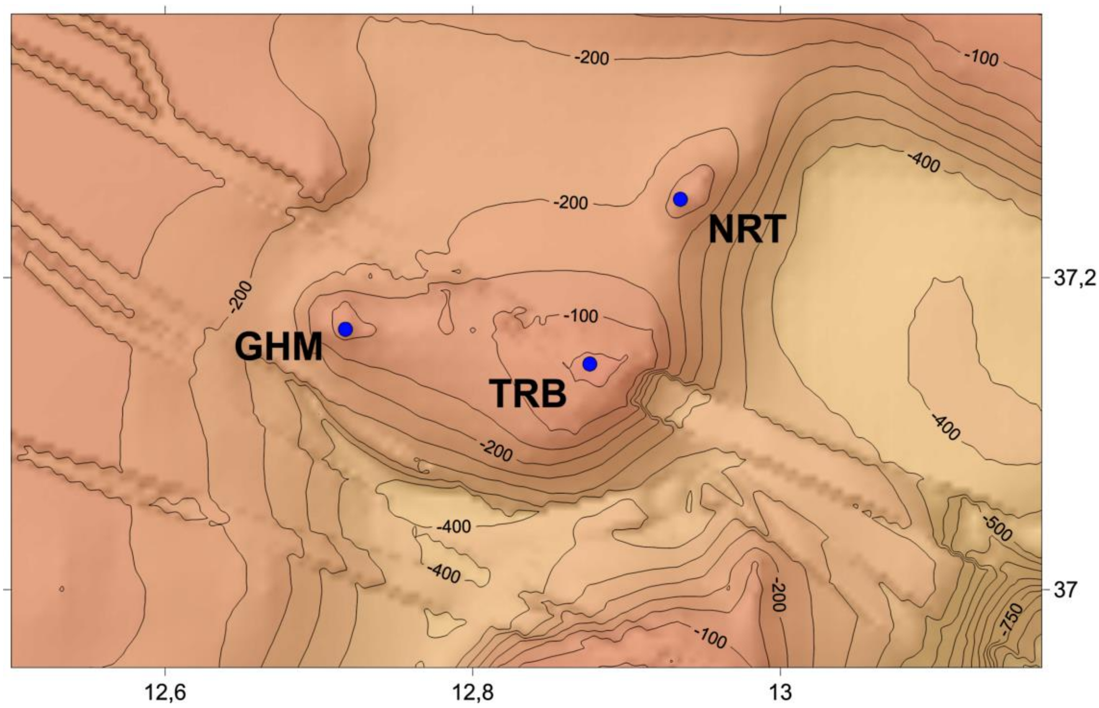

Fig. 5: Map of the Empedocle seamount, depth contours every 50 m. GHM, Graham bank; TRB, Terribile bank; NRT, Nerita bank.

The Pinne-Nameless Bank is a fault-bounded seamount located about 40 km SE of the Graham bank at the same latitude as Pantelleria. It is a Cenozoic carbonate platform split into two asymmetric sectors by a narrow valley at a depth of 200 m b.s.l. The largest plateau is 4 km in diameter (Fig. 6).

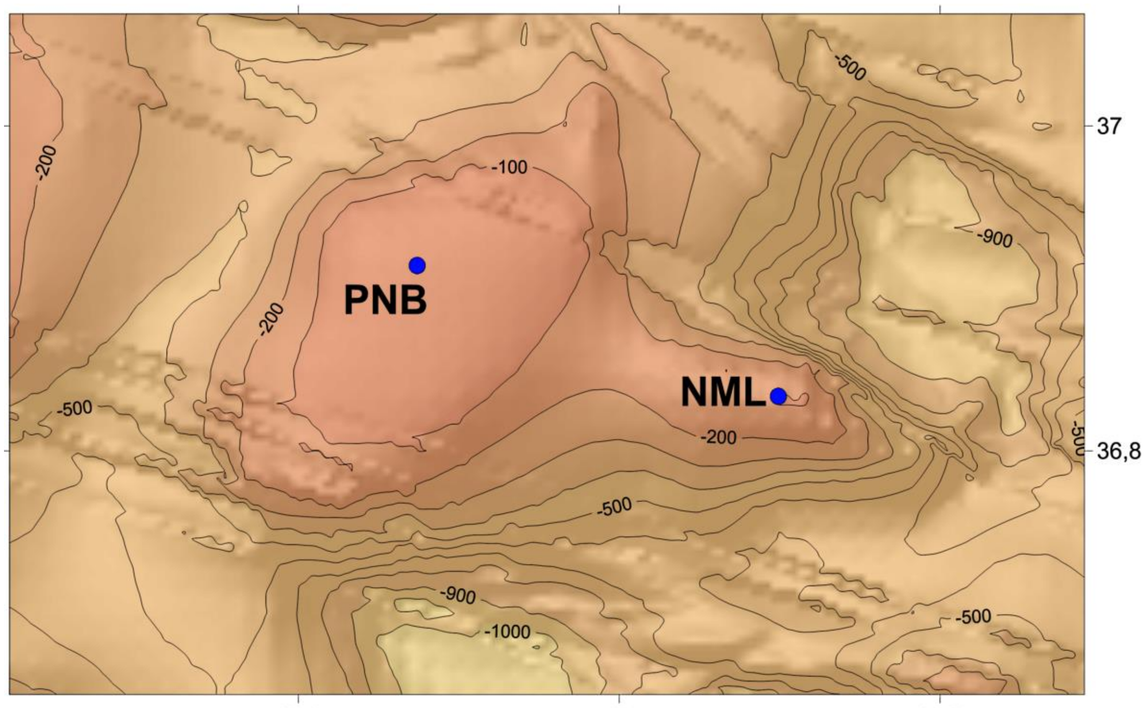

Fig. 6: Map of the Pinne-Urania-Nameless bank, depth contours every 100 m. PNB, Pinne bank; NML, Nameless bank.

According to Civile et al. (2008) and Civile et al. (2010), neogene rifting caused the development of three major depressions (grabens, basins or trough), the Pantelleria (1317-m depth), Linosa (1529-m depth), and Malta (1731-m depth), located in the central basin of the channel.

The Pantelleria graben, southeast of Pantelleria Island, is one of three narrow, steep-walled, elongate NW–SE troughs in the Channel. Pantelleria Trough has almost straight, fault-bounded slopes, over 100 km long and 28 km wide, with depths reaching 1314 m. Two fault valleys, running parallel and trending to southeast, cut the eastern end of Pantelleria basin.

One is the Linosa trough at the southern extremity of a graben system that trends south eastward from Linosa Island and probably is continuous with the Medina graben. At the eastern end of the Linosa graben three volcanoes raise from a depth of 500-700 m (Linosa I, II, III seamounts). The other valley is the Malta graben that trends parallel to the Linosa graben on its north-eastern side and to the south west of Malta. At its western end the Bannock seamount raises from about 800 m to 280 m depth, separating Malta graben from Pantelleria graben. The Malta graben separates Medina bank and Melita bank from the Malta platform on the north, which is part of the Pelagian block. Between these grabens is the prominent horst of the Malta seamount. A southward trending branch of the Malta graben, the Melita-Medina graben, separates the Melita bank from the Medina bank (Bishop and Debono, 1996).

In the southeastern parts of the Sicily channel, the African continental shelf is very wide and covers more than a third of the areal extent of the channel itself. In the Gulf of Gabes, the bathymetry is shallower than 30 m for large stretches away from the coast. This are correspond to submerged part of the Pelagian Province (Fig. 1) and encompasses other several major geologic structures. Among the more pronounced structural highs are the Lampedusa Plateau and Isis Horst.

The Ashtart-Tripolitania Basin (also called Gabes-Tarabulus Basin), Misratah Valley, Jarrafa graben are the major depressions. Fault systems, developed earlier in the Pelagian Province area (south of the Pantelleria graben, Malta graben, Malta graben), continued to sub-side and control deposition (Klett, 2001). Locally, relatively greater amounts of subsidence occurred in the Gulf of Hammamet. Orogenic movement is presently occurring in northern Tunisia (Burollet and others, 1978).

As an extensive, largely submarine platform, the Pelagian province is bounded on the northeast by the Ionian abyssal basin along the Malta escarpment, a system of normal faults of post-Miocene age that probably follows an older crustal fracture zone, and on the east – south east by the Sirte rise and the upper Sirte slope. The northern limit of the Pelagian province is the Calabrian fore-arc thrust zone, and on the northwest is the compressive Magrebid trend of Cap Bon. The Pelagian block was a stable promontory of the African margin throughout the plate tectonic history of the Central Mediterranean. Crystalline basement is continuous between Sicily and North Africa, and continental crust underlies the entire Pelagian realm. Stretching and thinning in the Sicily channel rift complex in late Miocene to Recent times results from transtensional dextral shear, and the dominant mode of deformation appears to be development of pull-apart basins (Klett, 2001).

2.1 Topographic features of remarkable biological relevance

2.1.1 Banks, seamounts and submerged volcanoes

Seamounts are considered as highly productive and biodiversity hotspots, since they produce retention areas for phytoplankton and create the conditions that support a diversity of important habitat types. According to a very recent census of the banks, seamounts and underwater volcanoes in the Sicily Channel carried out under the IUCN–MAVA PROMETEOS project (*PROtection of the MEdiTErranean Open Seas: Contributing to the establishment of Marine Protected Areas over offshore seamounts and submarine canyons*) this area is featured by several structures that can be classified as seamounts according to the definition given by Staudigel *et al.* (2010), who stressed that it is important to:

- Have a simple definition that explains which features are included under the umbrella of seamount research and which are not, providing an essential condition for defining the seamount research community,

- Respect and be aware of differences among disciplinary definitions, as they may stand in the way of consistently applying one disciplinary data set to another.

Geoscientists define seamounts as constructional features, so that formation processes are at the heart of their views and definition. Biologists define seamounts as habitats that are controlled by specific ocean environments, including the shape and summit depth of the feature studied.

Staudigel *et al.* (2010) have combined these diverse perspectives under one inclusive umbrella definition that describes seamounts as: *any geographically isolated topographic feature on the seafloor taller than 100 m, including ones whose summit regions may temporarily emerge above sea level, but not including features that are located on continental shelves or that are part of other major landmasses.*

According to this definition it is possible to identify at least 34 main structures of which it was possible to find the official name (tab. 1) and at least 9 more, likely banks, seamounts or volcanoes that have not been possible to find the name in the scientific literature or elsewhere (tab. 2).

BASE	CODE	LONG	LAT	PEAK (-m)	BASE (-m)
Adventure bank	ADV	12,17774	37,43741	20-30	190-200
Alfil-El Babouch bank	ALF	12,33391	35,84975	90-100	240-250
Anfitrite volcano	ANF	12,33998	37,25344		
Angelina smt	ANG	12,08318	36,70056	600-610?	990-1000?
Bannock smt	BNK	12,95061	36,47550	280-290	780-790
Birsa bank	BRS	11,68780	36,39810	80-90	190-200
Bouri bank	BUR	13,45112	35,38384	90-100	380-390
Cimotoe volcano	CMT	12,53249	37,00126		
El Haouaria bank	HRB	11,05010	37,31890	50-60	180-190
Empedocle smt	EMP	12,87937	37,14235	20-30	190-200
Epicharmos smt	EPC	16,58384	34,28377	250-260	1290-1300
Foerstner volcano	FST	11,89143	36,83669	90-100	340-350
BASE	**CODE**	**LONG**	**LAT**	**PEAK (-m)**	**BASE (-m)**
Fonkal bank	FNK	12,95400	35,51400	180-190	240-250
Galatea volcano	GLT	12,38967	37,21584		
Graham bank	GHM	12,71730	37,16678	0-10	190-200
Hecate bank	HCT	10,59860	37,66874	40-50	210-220
Keith reef	KTH	10,83178	37,79233	10-21	210-220
Linosa I volcano	LNS-I	12,73711	36,03317	590-600	690-700
Linosa II volcano	LNS-II	13,05265	36,05154	450-460	540-550
Linosa III volcano	LNS-III	12,95081	36,16757	400-410	540-550
Madrepore bank	MDP	13,38452	36,76370	270-280	580-590
Malta smt	MLT	15,01700	35,23324	80-90	390-400
Medina/Malte rdg	MDR	17,05067	34,91705	1090-1100	2320-2330
Medina bank	MDB	15,33660	34,99230	120-130	320-330
Melita bank	MLB	14,33338	34,33418	80-90	330-340
Nameless bank	NML	13,09928	36,83367	80-90	330-340
Nerita bank	NRT	12,93506	37,25028	10-20	190-200
Pinne bank	PNB	12,87395	36,91394	10-20	330-340
Pantelleria bank	PNT	12,11108	37,16355	40-50	190-200
Pantelleria E smt	PNT-E	12,37238	36,78434	600-610	990-1000
Pantelleria SE smt	PNT-SE	12,33385	36,43206	200-210	560-570
Pantelleria SW smt	PNT-SW	11,80079	36,63326	120-130	750-760
Pantelleria Central bank	CBK	11,89742	36,68456	620-630	750-760
Silvia knoll	SLV	11,02766	37,90426	20-30	210-220
Talbot bank	TLB	11,66642	37,36708	20-30	190-200
Terribile bank	TRB	12,87612	37,14468	20-30	190-200
Tetide volcano	TTD	12,29164	37,28298		

Table 1: List of the main known structures such as seamounts, submarine volcanoes, banks and other sea floor features in the Sicily Channel. The geographic coordinates have been estimated on the basis of the EMODnet bathymetry map, with 10 m depth interval at 450 m horizontal grid. Second column shows the codes reported in the figure 2 (blue dots).

COD	LONG	LAT	PEAK	BASE
1	11,28379	38,13380	120-130	380-390
2	10,63515	37,45867	50-60	190-200
3	10,79897	37,60927	80-90	200-210
4	11,25078	37,35827	120-130	300-310
5	11,46744	37,41904	50-60	240-250
6	11,33269	37,06234	60-70	210-220
7	11,55108	37,04971	130-140	400-410
8	11,73529	37,03383	230-240	400-410
9	12,69831	36,50845	710-720	950-960
10	12,58326	36,31815	550-560	760-770

Table 2: List of the unnamed structures such as seamounts, submarine volcanoes, banks and other sea floor features in the Sicily Channel. The geographic coordinates have been estimated on the basis of the EMODnet bathymetry map, with 10 m depth interval at 450 m horizontal grid. The first column shows the codes reported in the figure 2 (red dots).

2.1.2 Deep sea seeps, mud volcanoes and pockmarks

Hydrothermal vents, mud volcanoes and pockmarks are extreme environments characterized by different geochemical features and structural spatial complexity that can favour the presence of several sub-habitats within a single deep-sea seep. The heterogeneity, spatial complexity and variability of these structures play a role of the in time on maintaining the diversity and functioning of the deep benthic community.

On the Malta plateau (or Hyblean-Malta plateau) Savini *et al. (*2009) discovered by detailed acoustic mapping more than 100 small-scale domes and peculiar ridges were a few miles offshore between 140 and 170 m water depth. The investigated seafloor features have been interpreted as mud volcanoes and revealed different morphologies, in particular they are few meter high (no more than 10m) and are arranged on the seafloor in two main different styles:

1) several conical features of 50 - 200m in diameter, preferentially aligned along the isobaths

2) numerous close-set small cones up to 10m in diameter heavily colonized by gorgonians and appearing in video observation as carbonate structures, which are settled within well defined, flat, elongated areas (the largest one reaches 2000m in its long axis and 500m in its short axis) rising up to 10m form the seafloor.

Sea floor pockmarks are formed by gas discharge. They are features biologically relevant due the possible existence of unique chemosynthesis-based communities in the cold seep that are frequently found on them. Taviani *et al.* (2013) described a pockmark field located at ca. −800 m in the Sicilian Channel, at the West of the Gela Basin (the basin between

Adventure Bank and the Malta Plateau), such type of specialized deep-water cold-seep communities encompasses thiotrophic chemosymbiotic organisms (e.g. empty tubes of the vestimentiferan *Lamellibrachia* sp.; loose and articulated shells of lucinids, *Lucinoma kazani, Myrtea amorpha*; vesicomyids, *Isorropodon perplexum* and gastropods (*Taranis moerchi*). A callianassid decapod (*Calliax* sp.) was consistently found alive in large numbers in the pockmark mud.

Their post-mortem calcified parts mixed with molluscs and subordinately miliolid foraminifers form a distinct type of skeletal assemblage. It was found that the fluid seepage of this pockmark site has episodically sustained thiotrophic macrobenthic communities since the end of the Younger Dryas stadial up to sub-recent times.

3 Circulation System

Circulation inside the Sicily Channel is the consequence of the different hydrodynamic mechanisms affecting the region delimited by Tunisia, the Sardinia Channel and the Straits of Sicily as well as it is the results of those hydrodynamic processes inside the eastern Basin. The region offshore the North Tunisia coast forms the junction of three major subsets in the Mediterranean: the Algéro-Provençal Basin on the west, the Tyrrhenian Sea on the north and the East Mediterranean on the east (Ionian Basin). The transfers of water masses from one of these subsets towards the other are controlled by this common region. The water with an Atlantic origin (MAW) flows from the Algerian current through the Sardinia Channel and enters into the Sicily Channel through the Sicily Strait.

The Sicilian Channel is a high-energy site with a dynamic current system that exchanges the waters between the Mediterranean western and eastern basins and, as we have seen above, the influence of the strait geometry on the dynamics is very important.
Dynamically, the circulation in the Sicilian Channel can be described as an exchange of three main water masses (Fig. 7):

- The upper layer fresh modified Atlantic water (MAW), which enters through the Sicily channel as an extension of the north African Algerian coastal current and flows eastward, its northernmost branch is generally known as Atlantic-Ionian Stream (AIS);

- The Levantine Intermediate Water (LIW) that flows in the opposite direction mainly entering through the Medina sill to the southeast of Malta and, below the LIW;

- The Eastern Mediterranean Deep Water (EMDW) which, together with the LIW, forms the deeper eastern overflow water (EOW),

The general circulation is dictated by the slow basin scale (vertical) thermohaline structure of the Mediterranean, and carries a significant seasonal and inter-annual variability. In the upper thermocline the AIS characterizes the circulation by energetic meandering. The circulation is further modified by strong mesoscale signals in the form of eddy, meander and filament patterns.

These mesoscale processes are triggered by the synoptic scale atmospheric forcing. The heat and momentum fluxes at the air-sea interface represent the dominant factor in the mixing and pre-conditioning of the MAW on its way to the eastern Mediterranean.

3.1 The modified Atlantic water flow (MAW)

The MAW splits into two branches at the entrance to the Sicilian Channel, one flowing northward to the Tyrrhenian Sea, the other into the Sicilian Channel (Lermusiaux and Robinson, 2001). The second branch is composed by two streams, the Atlantic Ionian Stream (AIS) and the Atlantic Tunisian Current (ATC). According to Sorgente *et al*. (2003) and Drago *et al.* (2010) these two main branches of the MAW show a counter phase behaviour: ATC is stronger in winter and the AIS is stronger during summer .

The AIS starts its path as a meander to the south of Adventure bank. It then precedes south-eastward and loops back northward around Malta, forming along its path the Adventure bank vortex (eddy), the Maltese Channel Crest and, as it reaches the sharp Malta escarpment to the east, it abruptly gains positive vorticity and tends to deflect with an increase looping northward meander forming the characteristic Ionian Shelf Break Vortex (Fig. 7)

In summer, the AIS is associated with a number of well-known semi-permanent features including the intermittent northward extension of the AIS (NAIS) at the Ionian shelf break, which seems to be driven by the surface density contrast between waters of the Sicilian and the Ionian basins (Beranger *et al.,* 2004). The signature of the Modified Atlantic Water is seasonal and it is given by a salinity minimum (37.2) that is found at about 50 meters during summer and near the surface during winter (Manzella, 1988).

The northward flow along the Ionian shelf break is predominant during summer when the AIS is most intense and follows closely the Sicilian shelf break. The flow subsequently extends as a relatively strong velocity front into the northwestern Ionian where the summer circulation is mostly anticyclonic. The contrast in temperature of the MAW exiting the Sicily channel with the warmer Ionian Sea produces the Maltese front, which constitutes a conspicuous thermal filament on sea surface temperature AVHRR maps.

During winter, the MAW tends to spread more along the interior of the channel and it is more steeply sloped towards the African coast (Manzella *et al*., 1990), consequently the AIS is less intense. The exit of the MAW is shifted further south and progresses splitting into southeastward and southward branches. This situation is moreover favoured by an enhanced cyclonic component in the Ionian circulation especially during winter.

The circulation pattern in spring and fall is more difficult to assess. On the basis of more updated hydrographic data, (Robinson *et al*., 1998) it appears that the summer circulation pattern with a northward veering of the MAW over the Malta Escarpment is also common in both spring and fall. On the other end, earlier studies (Tziperman & Malanotte-Rizzoli, 1991; Ovchinnikov, 1996) concluded that on exiting the strait, the MAW will predominantly proceed to the north during summer and to the south and southeastward during the remainder of the year, while Zavatarelli & Mellor (1995) does not attribute very pronounced seasonal variability to the flow of the MAW into the Ionian Sea.

The path of the MAW is more complicated in winter than in summer. The analysis of the climatological buoyancy fields which actually indicate an intensification of the flow on the southern side of the channel during autumn and spring, whereas the flow is concentrated against the Sicilian side, reaching a salinity of 38.77.

The ATC feeds the circulation into the Gulf of Hammamet, where a cyclonic recirculation has been identified at 40 m depth. In summer, the waters of the Gulf of Hammamet are thus regenerated by the Atlantic water vein. In winter, the apparent convergence of surface waters towards the coasts of the Gulf as well as the flowing towards the South East of bottom waters suggest the establishment of a vertical agitation during this season.

North of the Lampedusa island, the Atlantic current splits in two branches: the first one towards the south-east and the second towards the south, feeding the circulation along the Gulf of Gabes. The flux presents a wellmarked seasonal variability (Manzella et al., 1988). The intensity of the second branch is consequently subject to fluctuations directly affecting local cyclonic circulation. The Gulf of Gabes occupies a vast region of shallow waters which are in thermal contrast with the waters from deeper regions in the east of the plateau. In these deeper regions the localisation of fronts corresponds to a bathymetric contour equal to the depth of the mixed water (40 to 50 metres).

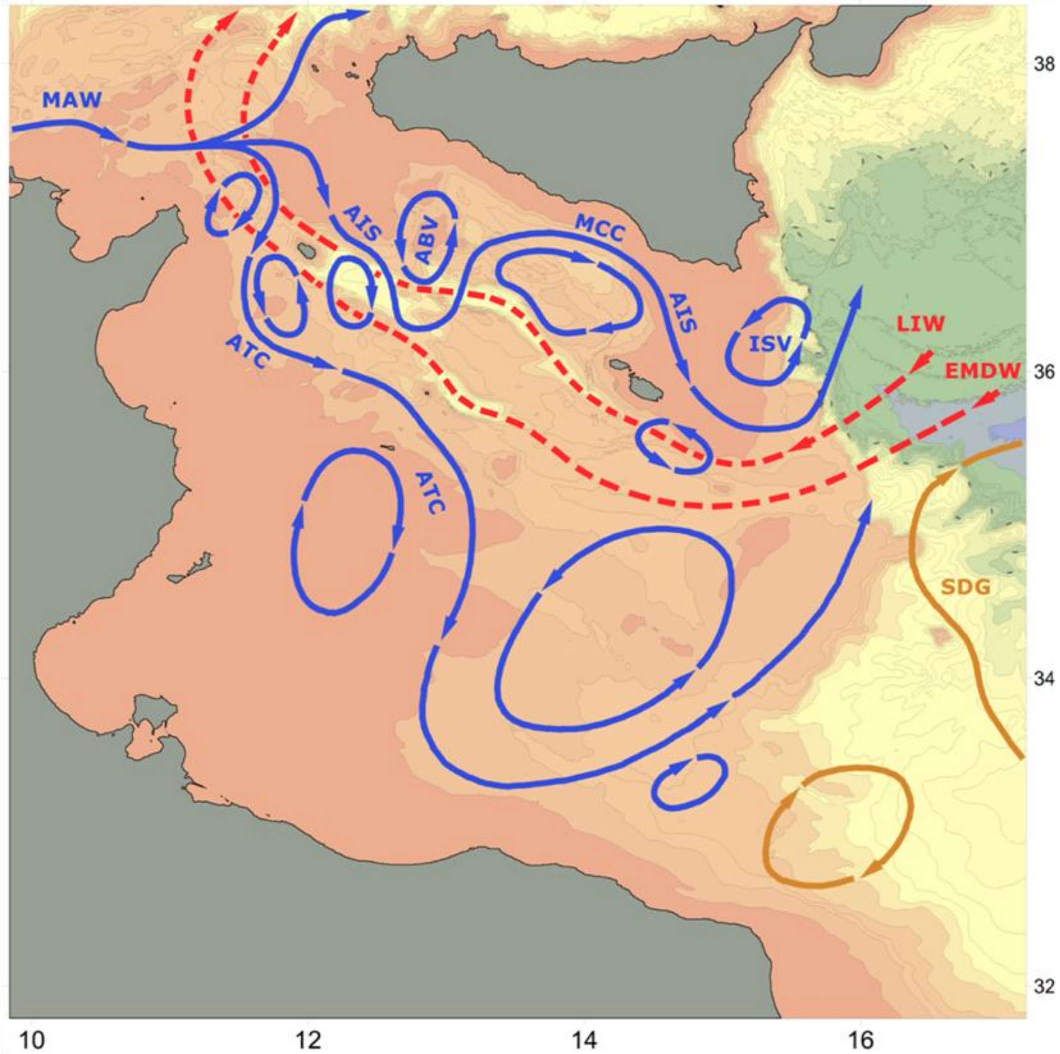

Fig. 7: A very simplified scheme of the flows crossing the Sicily Channel. The paths have been drawn according to the SSH map from myOcean average data for 2010-2013 period. MAW, Modified Atlantic Water; AIS, Atlantic Ionian Stream; ATC, Atlantic Tunisian Current; ABV, Adventure bank Vortex; MCC, Maltese Channel Crest; ISV, Ionian shelf break Vortex; SDG, Sidra Gyre; LIW, Levantine Intermediate Water; EMDW, Eastern Mediterranean Deep Water.

Warm anticyclonic eddies located on the south drive the ATC along its northern boundary. In winter, the anticyclonic structures contract in a stable nucleus (the Sidra gyre) close to the African coast allowing ATC intrusion over the Tunisian shelf. In summer, the anticyclonic structure expands westwards, limiting the ATC.

The ATC spreads into the central Ionian in summer but rarely in winter. Likely It reaches the northern Ionian Sea through anticyclonic eddies captured by the prevalent clockwise offshore circulation in the north-central Ionian (Ciappa, 2009).

3.2 Levantine Intermediate Water (LIW)

In the subsurface layers the topography plays an important role (Fig. 7). The LIW is formed mainly in the north eastern Levantine basin during winter as a result of cooling and evaporation processes and then it spreads westward at an intermediate depth, penetrating over the Central Mediterranean ridge and eventually entering the western basin after crossing the Strait of Sicily. The LIW has a higher velocity due to the Bernoulli effect: LIW has a narrow area to flow in comparison the wide area available to MAWs consequence, it enables the upper layer of the Eastern Mediterranean Deep Water (EMDW) in the Ionian sea to reach the western basin (Astraldi et al 2001; Gasparini *et al.,* 2005).

The core of the Levantine Intermediate water is indicated by a maximum at a depth of about 300 meters with a temperature of 13.75 - 13.92°C and a salinity of 38.73 - 38.78 psu at the channel. The Levantine Intermediate water has maximum salinity in the western and southwestern approaches of Malta. The renewal time of the total Levantine water in the strait is estimated to be 9 months, long enough to maintain a fairly constant salinity over the annual cycle. This also indicates that the characteristics of the Levantine Intermediate water incident into the strait from the eastern Mediterranean are also quite stable.
Upwelling along the eastern and southern costs of Sicily is a permanent feature. As explained by Beranger *et al.,* (2004), upwelling is governed by the south-eastward winds and by the inertia of the isopycnal domes of the AIS meanders and cyclonic vortices that can extend its influence far offshore due to the configuration of the circulation.
Many eddies of variable strength, shape and size (cyclonic and anticyclonic) are noticed in the Tunisian–Sicily region. According to Savini et al (2009) between Adventure Bank and the Malta plateau, LIW forms a pair of subsurface eddies (one cyclonic, one anticyclonic) along the western flank of the Malta plateau and AIS forms a cyclonic vortex off Cape Passero. The flux of LIW is not constant but subject to a seasonal variability and calculated to be 2–3 times higher in winter with respect to summer. The thickness of the LIW layer changes substantially with the seasons, wider in fall-winter and thicker in spring-summer.

3.3 Eastern Mediterranean Deep Water (EMDW)

The deeper Eastern Overflow Water (EOW) represents the water incident from the eastern Mediterranean overflowing over the south–central Mediterranean ridge into the Tyrrhenian Sea. It consists of LIW and Eastern Mediterranean Deep Water (EMDW), which is colder and fresher than the LIW. Below the LIW there is a significant volume of transient EMDW (tEMDW). In the Straits of Sicily area the tEMDW appears as a colder and fresher water mass with respect to the LIW, having a core characterised by a minimum temperature of 13.63°C and a salinity of 38.73.

The topography mainly shapes the intermediate and bottom circulations, which show almost, stable situations. The spreading westward water masses constitute an undercurrent which, spilling over the sills of the Straits of Sicily, partially compensates the transport of the upper flow and bring salty and warm waters into the Western Mediterranean.

The horizontal distribution of these multiple water masses gives evidence to the strong mixing processes in action. This system constitutes the basin scale thermohaline core of the Mediterranean circulation. The presence of the different water masses, their paths, and their interactions are the result of local (such as upwelling, meandering and eddies) and large-scale effects.

4 Sea Temperature

The seasonal and inter-annual variation of the water mass dynamic and distribution can be practically followed by their temperature signatures, both vertically and horizontally, when there is water stratification in the summer and water mixing in the winter period.

The main driving processes are: the progression of the AIS and its eastward extension, the upwellings south of Sicily, the warming and cooling of the shallow continental shelf waters. Indeed, significant variability can be observed from year to year and even the annual cycle is rather complex. When considering the simulated results of Sorgente *et al*. (2003) for seasonal variability of sea surface temperature (at 5m depth), figure 8 shows a shift in the mean temperature of about 6°C between winter (February) and summer (August) mainly as a consequence of surface heating.

During winters the mixing processes result in the homogenization of the water column up to depths in excess of 100m, and with temperatures on average 0.5°C higher in the southern part of the Sicily Channel. During this time, the thermal structure is fairly homogeneous, especially beyond 35° N (including the north side of the Sicily Channel). The temperature does not exceed 15°C.

During the summertime, the nearshore well stratified surface layer (averages 20m in depth) above the cooler and relatively fresher Modified Atlantic Water (MAW), due to solar heating, reaches temperatures between 20 and 26°C. In summer the simulated potential temperature is characterised mainly by upwelling events along the southern coast of Sicily, bringing cooler water to the surface. This is in contrast to the overall increase in temperature over the region.

Warm waters have a mean temperature of over 26°C. The contrast in temperature of the MAW exiting the Sicilian Channel with the warmer Ionian water produces a sharp temperature gradient which is often evidenced over the Malta escarpment by conspicuous thermal features on the sea surface temperature. The progression of the AIS and its south-eastward extension is delineated by the annual mean 19.86°C isotherm.

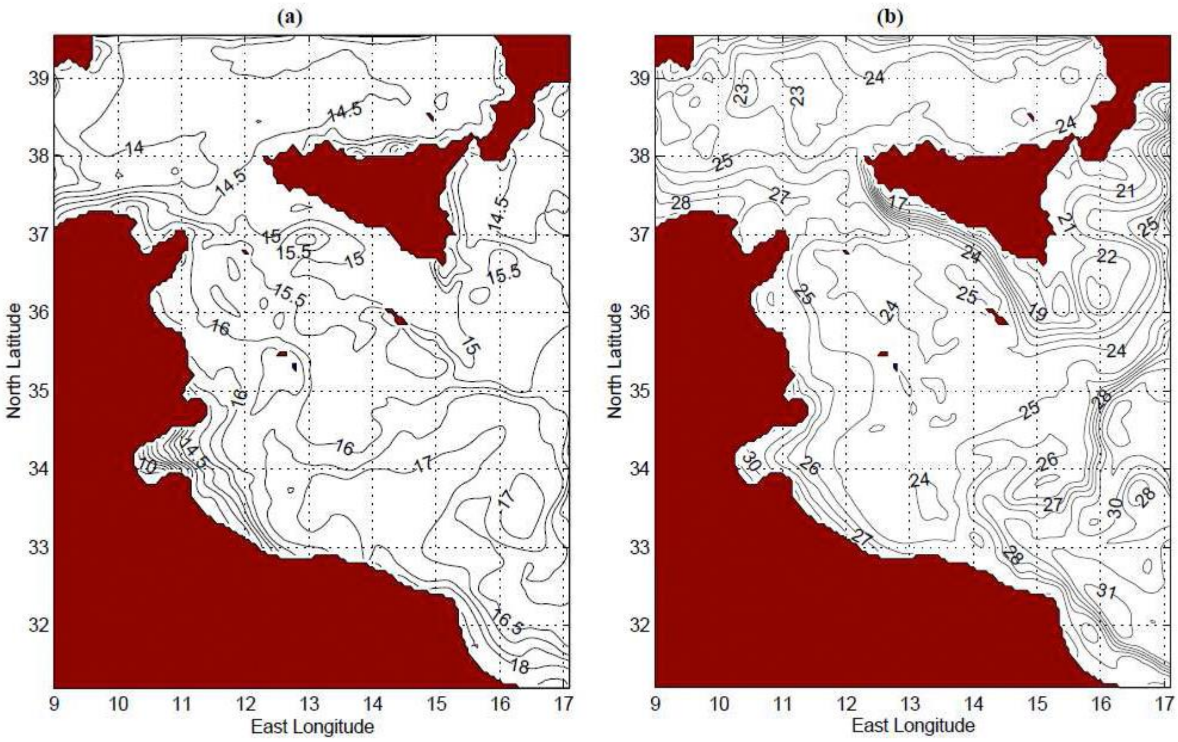

Fig. 8: Simulated 10-day averaged temperature field at 5m depth in (a) February & (b) August. Contour interval is 0.5° in February and 1°C in August (Sorgente *et al*., 2003).

5 Effects of Physical Parameters on the Biological Components

In the following paragraphs four main case studies are discussed in order to give examples about the effects of topography and hydrodynamics processes on the biological component of the Sicily Channel and Tunisia plateau. Of course these examples are not exhaustive; nevertheless other case studies about benthic and pelagic communities (i.e. some commercial target species) are outside the objectives of the contract for this review.

5.1 Deep sea coral habitats

In the central area of the Sicily channel, from the Pantelleria Island to the Malta Escarpment, NW-SE trending steep walled troughs and seamounts dominate the seabed landscape affecting both the incoming flows at the surface layers (MAW) from the west and at the deeper counter flow from the east (LIW). Turbidites from Lower Pliocene and Pleisticene fill these troughs, which are bounded by subvertical faults.

On the southeastern side of the Linosa trough impressive escarpment forms a near-vertical wall measuring 150–200 m in height. On the northeastern side of the trough the escarpment flanks a large pelagic mud covered plateau, at the depth of about 400–500-m, which separates the Malta trough from the Linosa trough. These bottom structures form a major topographic obstacle for the westward-flowing LIW.

The bottom current flows seem strongly influenced by the morphological features of the seafloor and this interaction affect the spatial distribution of sediment drifts and thus the biogenic build-ups. In this case the flow of the LIW and the transitional Eastern Mediterranean Deep Water directly impinging onto the area of active coral growth centred at ca. 450-600 m. Healthy and well developed deep-sea coral mound (mainly *Lophelia pertusa* and *Madrepora oculata*) community may take advantage of the current-advected food supply (Freiwald *et al.* , 2009; Martorelli *et al.,* 2011).

The main sites, where healthy deepwater coral banks have been recently recorded, are shown in Fig. 9 (Bussoletti et al., 2010; Freiwald et al., 2009; Martorelli et al., 2011; Scembri et al., 2007; Taviani et al., 2011; Zibrowius and Taviani, 2005).

South of Malta, in a depth range of 390-617 m, samples revealed thick fossil coral frameworks with overgrowing coral assemblages mainly consisting of *M. oculata* and *L. pertusa* associated with *Corallium rubrum* (here in the Sicily Channel at the known deepest range), also *Dendrophyllia cornigera* was detected in some samples, and gorgonians (Vella and Vella, 2012). The symbiotic polychaete *Eunice norvegica* was found to inhabit the colony bases.

On the Linosa trough, between 803–536-m depth, have been observed both the fossil and live coral communities thriving under overhangs and in large caves, and they were particularly common in volcanic bedrock sequences, while on the neighbouring plateau, where the mud has been observed to be bioturbated by crustacean burrows and by grazing tracks of holothuroids and cidaroid echinoids, the sessile benthos is dominated by the octocorals *Isidella elongata* and *Funiculina quadrangularis.*

In the Urania-Nameless Bank, from 654 to 440-m water depth, the colonies of *M. oculata* measured up to 70 cm high and 50 cm wide, while those of *L. pertusa* rarely exceed 10 cm in size (Freiwald *et al.* 2009).

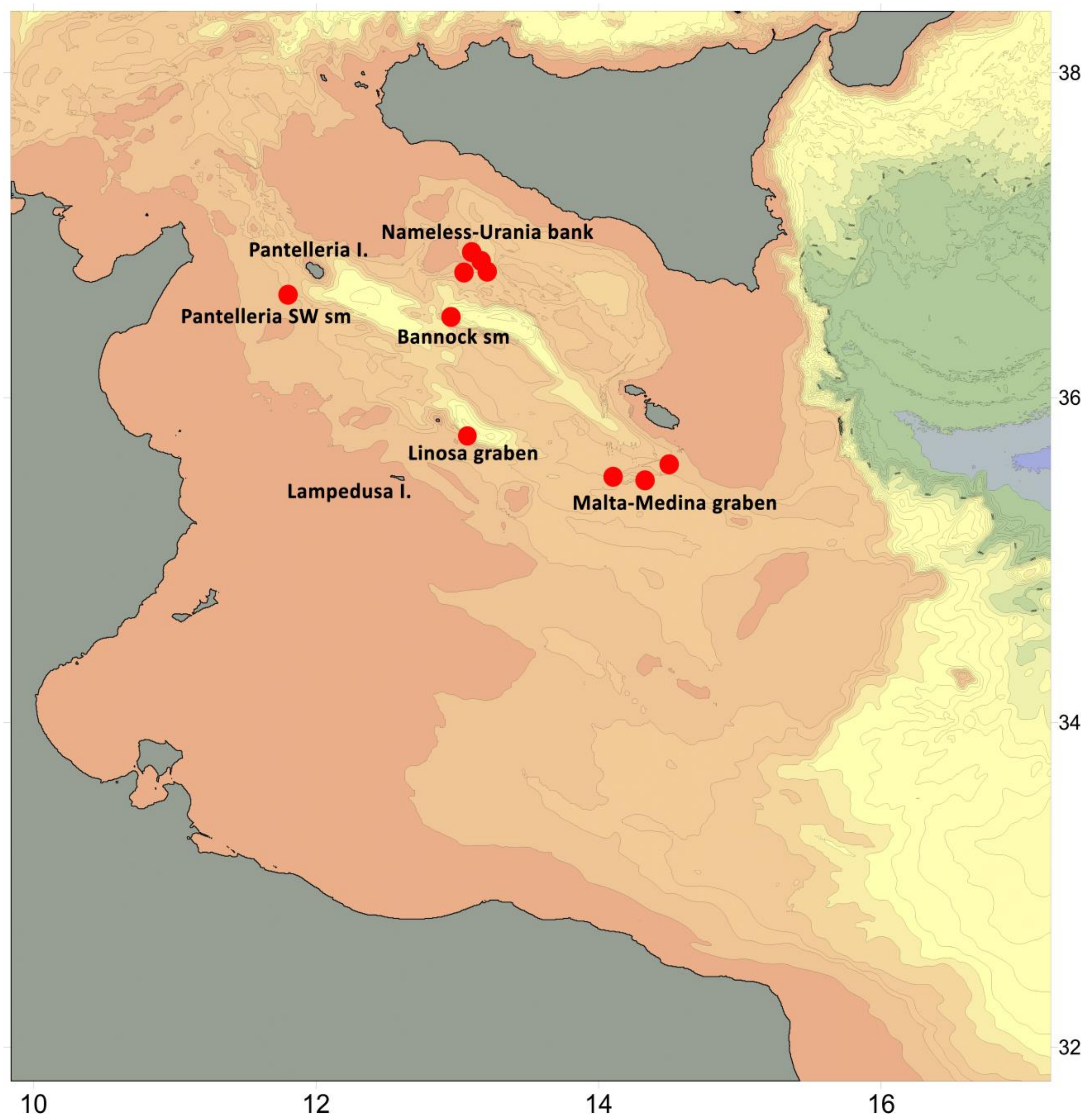

Fig. 9: Locations of the healthy deep coral communities as described by Bussoletti et al., 2010; Freiwald et al., 2009; Martorelli et al., 2011; Scembri et al., 2007; Taviani et al., 2011; Zibrowius and Taviani, 2005

The deep-water corals habitats are rich in species diversity, in fact a total of 51 benthic species, among them poriferans, cnidarians, brachiopods, mollusks, polychaetes, crustaceans, and echinoderms, have been recorded, where the deep-water corals are located in the above mentioned three main areas (Zibrowius & Taviani 2005; Schembri *et al.* 2007; Freiwald *et al.* 2009). Overall, coral habitats support or share the environment with other deep-sea macrofauna among which the large limids (*Acesta excavata*) and giant oysters (*Neopycnodonte zibrowii*). Live and dead colonies of *Madrepora* and *Lophelia* can support epibionts such as hydroids, *Spondylus gussonii*, serpulids, the solitary coral *Desmophyllum dianthus,* the barnacle *Pachylasma giganteum,* while the bivalve *Asperarca* nodulosa has been collected from between the branches of dead *Lopehlia* and errant species included the echinoid *Cidaris cidaris*, the gastropod *Coralliophilia richardi,* and the crab *Anamanthia rissoana*.

The structural complexity of the deep-water coral reefs, acting as essential habitats for feeding and spawning, can also attract cephalopods, crustaceans, and fishes, as well as studies on prokaryotic assemblages associated with the deep-sea coral *Lophelia pertusa* in the Central Mediterranean Sea revealed specific and unique microbial assemblage (Danovaro, 2010).

5.2 Ocean triads and the effect of AIS on anchovy spawning

In the Mediterranean Sea, summer has been found to be the only season of the year not characterized by very high rates of mechanical energy added to the water column by the wind. Hence, during the rest of the year, turbulent mixing intensities are high in areas exhibiting linked enrichment and concentration processes, and appear to preclude conditions that may characterize favourable reproductive habitats. Other areas, however, have been found representing apparent large-scale *ocean triads* during the summer season. They can then be considered as potentially very favourable reproductive habitats, considering the arrangement of physical mechanisms. The Sicily Channel is one of the areas found by Agostini and Bakun (2002) where *ocean triads* - e.g. enrichment processes (upwelling, mixing, etc.); concentration processes (convergence, frontal formation, water column stability) and processes favouring retention within (or drift toward) appropriate habitats - are located. In the Mediterranean Sea, *ocean triads* appear to be associated particularly with summer conditions, and interestingly, summer is also the seasonal spawning period for anchovies and sardines, as well as other important pelagic fish such as tunas (Agostini and Bakun, 2002, Iglesias *et al.*, 2003).

It has been difficult to locate much of the information published on anchovy reproduction off Tunisia. Anchovy eggs were found and reported in a survey conducted in 1972 (Ktari-Chakroun, 1979), but in spite of their comparatively high values, anchovies, even during that period, never attained more than 9% of the pelagic landings in the area.

Anchovy spawns along the narrow shelf off the southern Sicilian coast, from Sciacca to Gela (Garcia-Lafuente *et al.,* 2002). The most important spawning ground is located off Sciacca, where a branch of the Atlantic Ionian Stream (AIS) impinges the coast.

Other places can provide similar favourable spawning conditions, such as the region off Cape Passero. East of Cape Passero, the continental shelf drops sharply and by lateral friction with the coastline to the left side of the jet, it makes a northward bending with a cyclonic circulation cell of the AIS, flowing into the deep Eastern Mediterranean Basin (Fig.

65). This area could act as a retention area with low current velocities. A second area of low flow velocities is the southeast end of the Gulf of Gela, off Sicily, due to the detachment of the AIS from the shore, as observed from the general circulation pattern.

Larval distribution shows the role played by advection. Larval abundance and larval size increase towards the southeast (Fig. 65), and Cape Passero not only registers maximum larval densities but also larger individuals. On the other hand, the locally unbalanced ratio anchovy eggs/anchovy larvae in this zone indicates that the larvae did not hatch there, but were advected from other areas.

High larval concentration observed by Garcia Lafuente *et al.* (2002) off Cape Passero raises the question of whether there are physical reasons for defining it as a retention area. As shown in Figure 14, the general surface circulation of the AIS generates vortices. These result in the formation of a series of anticyclonic and cyclonic vortex off the southern coast of Sicily and Malta. The maintenance of cyclonic vortex implies the existence of upwelling at its centre to counterbalance the effects of friction. This is a suitable condition for sustaining high rates of primary production. Convergence generated by anticyclonic eddies southeast of Cape Passero allows the larvae to maintain their relative position in an area where retention also provides favourable conditions for larval feeding and growth.

5.3 Bluefin tuna (*Thunnus thynnus*) spawning area

Tuna are known to spawn in SSTs above 24°C. In the Levantine Sea, SSTs values between 22.5 and 24.9 C are generally recorded from the second half of May, while in the eastern Mediterranean, the reproductive season of bluefin tuna starts almost 1 month earlier (mid-late May) than in other Mediterranean spawning grounds (June-early July). Several years of investigation on bluefin tuna larvae distribution, as well as studies on the presence of females with hydrated oocytes and post-ovulatory follicles, have not sufficed to complete the map of spawning areas in the Mediterranean. Large knowledge gaps mainly exist for the eastern basin, where an important spawning ground has been recently identified North of Cyprus (Karakulak *et al.*, 2004) (Fig. 53).

According to the results of larval campaigns, bluefin tuna spawn within a large portion of the pelagic Mediterranean environment (Piccinetti *et al.,* 1997; Nishida *et al*. 1997; Tsuji *et al.,* 1997). Remarkable concentration of eggs and larvae occurs south of the Balearic islands, around Malta, off the eastern coast of Sicily and in the South Tyrrhenian Sea, where hydrological features are more favourable for their survival (Charbonnier and Garcia, 1985) (Fig. 54).

As shown by tagging campaigns (De Metrio *et al.*, 2004), movement of *T. thynnus* within the Mediterranean Sea is often limited, particularly for individuals tagged in the eastern regions of the basin. It seems that movement of bluefin tuna tagged in the central and western Mediterranean Sea are more pronounced than in the east. Seasonal prey abundance (e.g. *E. encrasicolus, S. pilchardus, M. norvegica, S. scombrus, A. rochei*, etc.) drives the concentration of both young and adult specimens in Mediterranean areas not used for reproduction.

Surface fronts can affect the spatial aggregation of bluefin tuna schools, at least at certain scales. Shelf-break fronts can be seen all around the basin and very close to the shore, where the continental shelf is narrow. Coastal fronts are also visibile along the southern Sicilian coast.

The Gulf of Gabes in Tunisia shows a decline in frontal density during September, possibly linked to tidal phenomena. The association between the distribution of juvenile bluefin tuna schools and thermal fronts was found valid only over a limited range of spatial scales (10-40 km). This indicates that other processes occur on small scales (over-aggregation due to unseen prey clusters or other behavioural processes) and larger scales (in and out movement at the border of the studied area).

The relationship between tuna aggregates and frontal meanders is most probably indirect and trophic-related. Advected material at fronts can provide favourable feeding grounds for small clupeids, which are in turn sought by bluefin tuna. Interannual and seasonal variations in frontal density in the Mediterranean Sea may not have a direct influence on the basin's global carrying capacity. However, it may have an important impact on the local aggregation of nutrients, phytoplankton and zooplankton species, and eventually on fish schools, thus leading to possible changes in density-dependent responses in marine populations. Transient surface fronts are particularly difficult to observe and assess (Royer *et al.*, 2005) (Fig. 54).

Koched *et al.* (2012) have studied the spatial distribution and ecology of the larvae of three tuna species (*Thunnus thynnus, Auxis rochei* and *Euthynnus alletteratus*) in the Gulf of Gabes. The *A. rochei* (bullet tuna) larvae showed a more widespread distribution than the other species, being found at both inshore and offshore stations. *E. alletteratus* (Atlantic black skipjack) larvae distribution covers a wide area over the continental shelf of this region. The larvae of the large migratory tuna *T. Thynnus* (Atlantic bluefin tuna) were mainly sampled from the offshore stations, suggesting that spawning possibly takes place mainly near the shelf break. Tuna larvae were mainly collected in oligotrophic and mixed waters resulting from the confluence of surface water of recent Atlantic origin (ATC) and resident surface Mediterranean waters, as shown by their preference for lower chlorophyll *a* concentrations (from 1.4 to 2.5 mg m-3) and moderate salinity values (between 37.35 and 37.75). Significantly, tuna larvae seemed to avoid the more eutrophic and saltier waters of the gulf situated very close to the coast and around Kerkennah and Djerba islands.

5.4 Fin whale (*Balaenoptera physalus*) winter feeding ground

The winter feeding ground of the Mediterranean fin whales has been identified by Canese *et al.* (2006; Aïssi *et al.,* 2008). Fin whales have been observed to feed mainly on the euphausid *Nyctiphanes couchi* swarms formed over the large area within the Lampedusa plateau (Tunisia shelf), mainly on the south and southeast side of the island (Celona, personal communication) Even if no further investigations have been carried out in order to understand the oceanographic processes driving the high concentration of that euphausid species, it is possible to draft some hypotheses on the light of the bottom topography and circulation patterns previously described.

The Lampedusa plateau is bounded to the northeast by the Linosa graben, which is connected to the deeper Ionian plain by its branch Medina–Melita graben, while on the south Jarrafa graben deeply incises the 200 m bathymetry of the plateau creating the favourable conditions for the shelf-deep bottom exchanges. According to the general circulation schemes and models (Astraldi *et al.,* 2001; Sorgente *et al.,* 2003; Ciappa, 2009; Molcard *et al*., 2002) it can be roughly stated that the ATC flows following the shelf rims in that area meandering and generating cyclonic eddy on its left (eastward) over deeper waters and anticyclonic eddy on its right (westward) over the shelf (Fig. 8).

Cyclonic eddies generate upwelling, while anticyclonic eddies create downwelling and retention, it is possible to argue that the upwelling transport is also enhanced by the funnel effect of the above mentioned valleys (grabens), which lies just below, thus nutrients are easily transported from the deeper bottom to the shelf, where are entrapped by the clockwise flow close to Lampedusa island.
Moreover this is also consistent with the observations done by Ciappa (2009) about the role of the Sidra gyre in modifying the ATC flow during the winter. Very likely, the plateau shallow waters enriched with the nutrients from the closer deep bottoms are a very favourable area for the grazing and/or herbivorous species, as *Nyctiphanes couchi* is. Similar topography-hydrodynamic effect have been observed in the Ligurian sea, where fin whales feed mainly on Meganycthyphanes norvegica from late spring to early autumn, even if onmuch more deeper water than in the Sicily Channel (Würtz, 2010).

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