

Bathyal zones of the Mediterranean continental slope: An attempt

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ABSTRACT

On the continental slope, the bathyal can be divided into two zones, the upper bathyal and the middle bathyal, at the shelf break, which represents the boundary between the coastal shelf environment and the deep realm, located at about 100-110 m depth. The upper bathyal, previously considered a transitional zone, is characterised by distinct physical, geological and biological features. Its bathymetric extension is directly related to slope physiography, and its lower boundary generally corresponds to the mud line. This belt is governed by specific abiotic factors with steep physical gradients (e.g., hydrodynamics, salinity, oxygen, temperature, sediments). Major change in the benthic fauna is associated with major change in these abiotic factors. The three main biocoenoses are dominated by suspension-feeding species, which are exclusive to the Mediterranean upper bathyal. Depending on water parameters, the limit between the phytal and aphytal systems generally occurs within the upper bathyal. The second zone, the middle bathyal, is poorly documented; however, it can be divided into several subzones whose limits appear to be related to water-mass characteristics: the upper-middle slope, the lower-middle slope, and the lower slope. The lower bathyal zone develops into the bathyal rise and plain.

Key words: Mediterranean Sea, continental slope, bathyal zonation, biological oceanography, physical oceanography, geological oceanography.

RESUMEN

Las zonas batiales del talud continental mediterráneo: un ensayo

En el talud continental, el piso batial se puede dividir en batial superior y batial medio. Su límite superior (100-110 m) corresponde al reborde del talud, situado entre dos dominios muy distintos: el de la plataforma y el profundo. Anteriormente considerada como «zona de transición» entre el piso circalitoral y el batial, el batial superior se caracteriza por sus particularidades físicas, geológicas y biológicas. Su extensión batimétrica depende de la fisiografía del talud, que induce los efectos de los factores abióticos y así provoca una distribución del bentos en cinturones con dominancia de los suspensívoros y la casi ausencia de sedimentación. El batial superior comprende generalmente el límite entre el sistema fital y el afital según la transparencia de las aguas. El batial medio empieza a partir de la línea de fango (mud line) que marca un cambio abrupto de la energía. Aunque faltan estudios detallados, a partir de los datos disponibles se puede proponer un esquema de la zonación del batial medio: el talud medio superior, el talud medio inferior, el talud inferior. Por tanto, el batial inferior se extiende en la llanura batial.

Palabras clave: Mar Mediterráneo, talud continental, zonación batial, oceanografía biológica, oceanografía física, oceanografía geológica.

INTRODUCTION

The upper part of the Mediterranean continental slope was previously regarded as a «transitional» zone between the circalittoral zone and the bathyal zone (Pérès and Picard, 1964; Carpine, 1970; Reyss, 1974; Falconetti, 1980; Emig, 1985; Pérès, 1982; Bellan-Santini, 1983; Abelló, Valladares and Castellón, 1988). All these authors have noted the importance of the bathymetric depth range between 100-150 to 200-300 m, which generally includes the limit between the phytal and aphytal systems (Emig, 1989b). But they failed to take into account the importance of abiotic factors, i.e., slope physiography and physical characteristics, in order to explain the biological specificity of this zone (Emig, 1985, 1989a, 1989b) whose limits have never been clearly defined. However, Ercegovic (1957) and Pérès and Picard (1964) defined the extension of the «transitional» zone, from the lower boundary of the circalittoral, i.e., the lower limit of multicellular algae, down to the lower limit of unicellular algae. Consequently, the «true» bathyal zone was considered to begin beyond the transitional zone, between 200 and 500 m. Other authors use arbitrary (150 m) or economical (200 m) zone definitions of the upper limit of the bathyal, based on artificial considerations, never scientific ones.

A review of the northwestern Mediterranean bathyal zone, with new information from submersible campaigns along the continental slope, makes it possible to reconsider the position and importance of this zone on the continental slope. On the other hand, few faunistic surveys were performed in the Mediterranean bathyal, and comparisons of data and results are difficult, because they were obtained in different ways. Consequently, neither local nor biogeographic comparisons can be made. Nevertheless, except the upper bathyal zone, the other bathyal zones are unlikely to be defined and characterised at present, although a general tendency can be discerned.

Upper bathyal zone

The upper limit of the bathyal zone lies at the continental shelf break, defined by physical, geological and biological characteristics (figures 1 and 2). Although of primary importance, because of major gradient changes, the Mediterranean shelf-

edge sector is a poorly known environment because it lies between two distinct zones of interest, the coastal-shelf environment and the deep realms (figure 2). Thus, it is not surprising that the shelf-to-slope transition remains a biological and physical «no man's land» (Vanney and Stanley, 1983).

The Mediterranean shelf-to-slope morphology on soft substrates presents two major types of profiles (figure 1), on which the shelf break occurs at about 100 to 120 m. However, in Type II, the continental shelf break is generally considered to be at a depth of about 150 m, which corresponds to the edge of a large and flat bathyal offshore terrace; but the true continental shelf break, often missed, lies shoreward and corresponds to the edge of a short scarp of about 5-20 m (figure 1) (Emig, 1989a, 1989b; Savoye and Piper, 1993).

The lower limit of the upper bathyal zone is indicated by the mud line, which is known to indicate an abrupt change in the environmental conditions (Blake and Doyle, 1983) and serves as an energy-level marker (Stanley, Addy and Behrens, 1983). Located a depth of between 160 and 300 m, this limit is related directly to slope morphology (figure 1), which governs the influence of the prevailing abiotic factors: the weaker the incline the shallower in depth is this limit (Emig, 1989a, 1989b). Thus, like the upper limit of the upper bathyal, the lower limit does not coincide with a bathymetric expression.

Physical characteristics

The upper bathyal zone is a high-energy sector characterised by gradient variations of the prevailing abiotic factors, i.e., hydrodynamics, salinity, temperature, oxygen, sediments (figure 2). In the entire northwestern basin there is a main current, the Liguro-Provençal-Catalan current, that follows the continental shelf break and coincides with a permanent shelf/slope density front; this flow is intensified by the prevailing winds and separates the continental fresh waters on the shelf from the saltier and usually warmer open-sea waters (Salat and Font, 1987; Millot, 1987; Wang *et al.*, 1988; Emig, 1989a; Monaco *et al.*, 1990; Font, 1990; Emig and García-Carrascosa, 1991; Huthnance, 1992).

The near-bottom current, weak or absent on the lower part of the continental shelf, increases by several tens of meters at the level of the shelf edge; its

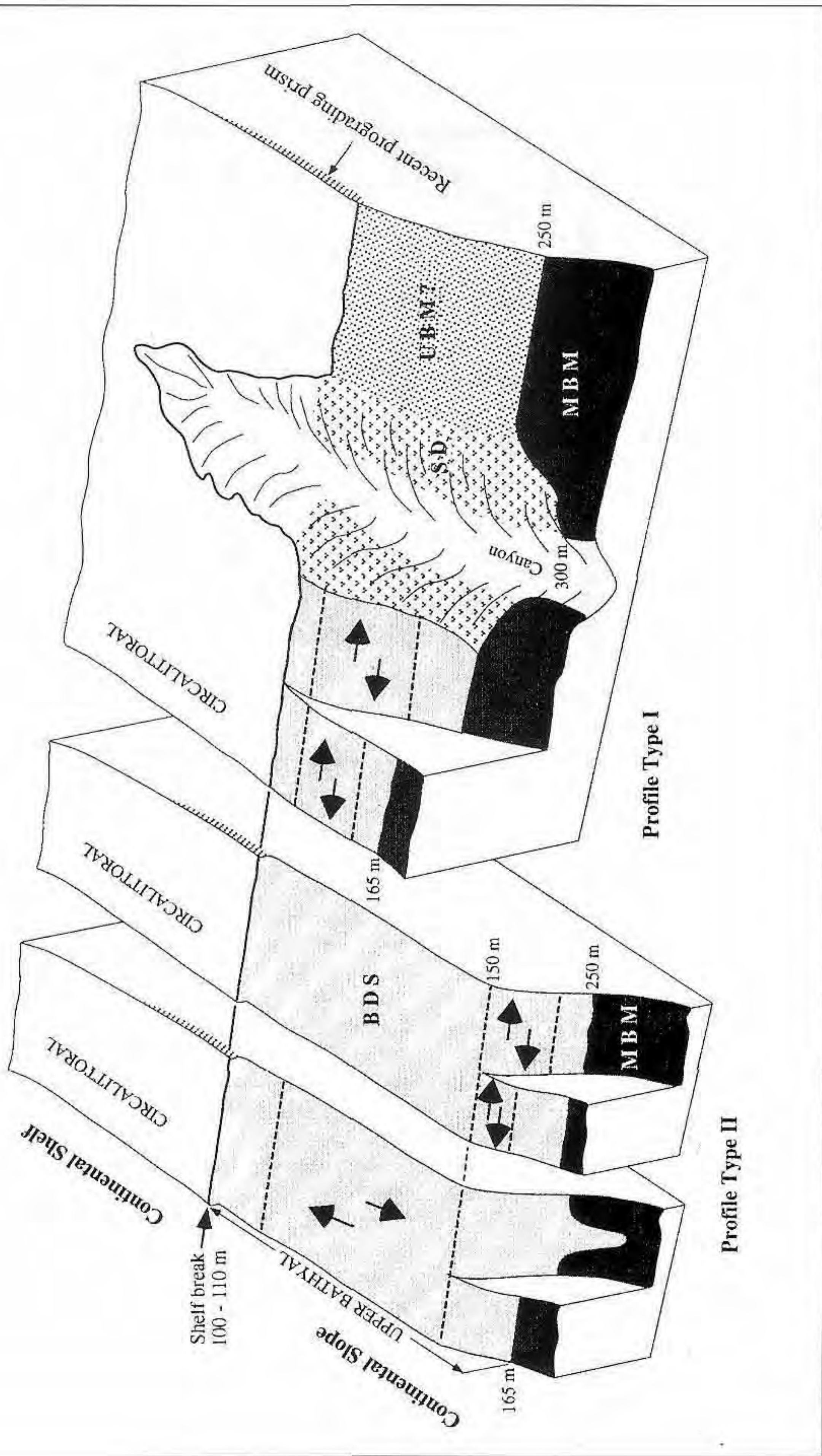


Figure 1. Block-diagrams of the bathyal biocoenoses distribution along the upper continental slope sector according to the slope gradient on the two main profile types, I and II, with the sides showing the sedimentation prism since the last Würm glaciation (hatching). For profile locations (Provence and Corsica) and explanation see Emig (1989a, 1989b, 1989c), Emig and García-Carrasco (1991). The numbers indicate the depth in metres. Between dotted lines, the strongest velocity zone of the near-bottom currents and their main directions (arrows). Biocoenoses: (UBM): upper bathyal mud; (SD): shelf detritic; (BDS): bathyal detritic; (MBM): middle bathyal mud.

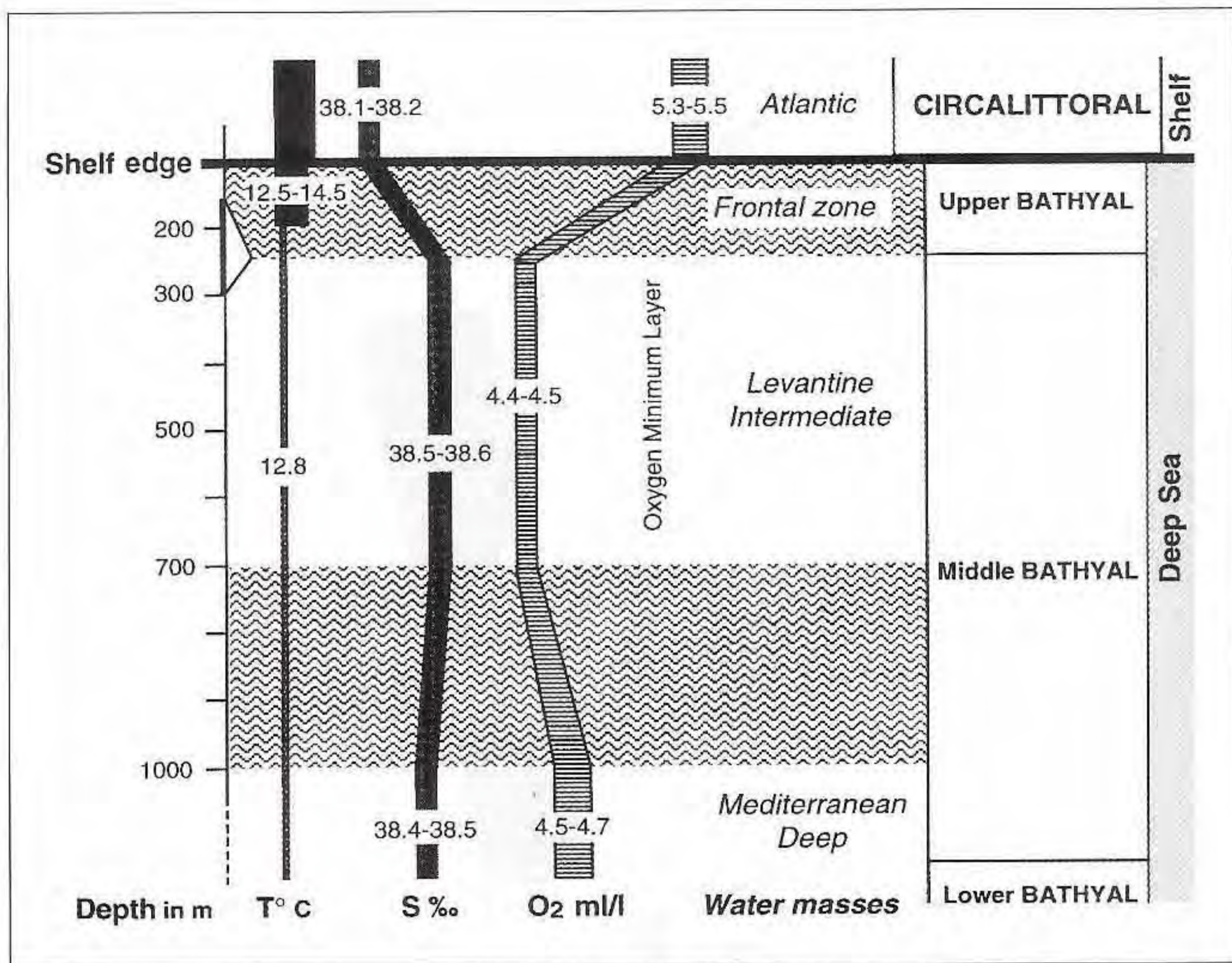


Figure 2. Diagram of different parameters of the surrounding water column in the Bathyal Zone (drawn after data from various authors).

bathymetric extension, velocity and direction are directly related to slope physiography (figure 1). The velocity shows a vertical gradient (figure 1) and varies from about 0.5 up to 2 knots or more, and sometimes causes large ripple marks or undulations on the bottoms (Reyss and Soyer, 1965; Emig, 1987). Consequently, sedimentation is absent or weak in the upper bathyal, which appears to be a resuspension zone with minor accumulation of particles and in which the fauna is characterised by high densities of suspension-feeders. At the lower limit of the sector, the bottom current velocity drops off by several tens of meters, while the substrate becomes muddy (Reyss and Soyer, 1965; Emig, 1989a; Emig and García-Carrascosa, 1991): the mud line is easily detected in the case of a change from sandy to muddy substrates, but remains problematical when this line occurs shoreward to the shelf edge.

In the surrounding water column several other gradients characterise the upper bathyal in

the northwestern Mediterranean Sea (figure 2): low annual temperature variation (about 2 °C) which becomes constant beyond about 200 m depth (the Mediterranean homothermy), low salinity increase, and sharp decrease of oxygen which, however, is known to be higher than biological consumption. The lower boundary corresponds to the lower limit of the frontal structure, across which the hydrological properties change sharply (Huang and Su, 1991), and to the beginning of the oxygen minimum layer (OML) which is related to the Levantine intermediate water mass with a salinity maximum and homothermy (figure 2).

The C/N ratio in the sediments decreases from 12 to 10 (Carpine, 1970). The change of sediment occur in some tens of meters, related to the hydrodynamics, at both limits of the Upper Bathyal (Emig, 1989a; Emig and García-Carrascosa, 1991).

Geological characteristics

The Recent imprint, since the last rise in sea level (the Würm glaciation, 17 000 years), is clearly evident in the upper bathyal: the continental shelf break lies at the outer edge of the deposits forming a narrow prograding wedge or prism located at the outer part of the continental shelf (figure 1). The shelf edge is in equilibrium with the present environmental conditions; its progradation during the Late Holocene has been negligible and its depth coincides with a «depositional equilibrium» level (Mougenot, Boillot and J. P. Rehault, 1983; Monaco *et al.*, 1990; Courp and Monaco, 1990; Savoye and Piper, 1993). The relative absence of Recent sediment supply in the upper bathyal (figure 1) shows that sediments are mainly reworked relict (Würmian) sediments with the occurrence of Quaternary thanatocoenoses visible by submarine observation and generally located at a depth of between 180 to 200 m (Gautier and Picard, 1957; Blanc, 1968; Emig, 1987).

Biological characteristics

The circalittoral extends down to the lower limit of multicellular algae (Pérès and Picard, 1964): from submarine observations of the coastal detritic biocoenosis (CD), calcareous red algae do not extend beyond the shelf-break and, after a short transitional zone of some tens of meters, the bathyal detritic sand biocoenosis (BDS) begins, or at the sides of submarine canyons, the shelf-edge detritic biocoenosis (SD) (figure 1). The SD has been traditionally considered a circalittoral biocoenosis, sometimes confused with the BDS, but belongs without any doubt to the upper bathyal (Laubier and Emig, 1993). The continental shelf edge corresponds to the upper limit of the distribution of at least two exclusive upper bathyal species, the brachiopod *Gryphus vitreus* (Born, 1778) in the BDS and the crinoid *Leptometra phalangium* (Müller, 1841) in the SD, while the mud line corresponds to the lower limit of their extension.

The substratum of the BDS is well-sorted sand (gravel, coarse and fine sand), clogged by a fine fraction which can reach 60 %, and contains a large detritic proportion of small hard substrates of endogenous origin (fragments of mollusc and brachiopod shells, of sponges, bryozoans, corals, grav-

els and pebbles), a characteristic of the BDS bottom (Falconetti, 1980; Emig, 1989a, 1989b). The substratum of the SD is sandy mud (gravel, sand, mud) (Picard, 1965; Emig, unpublished data).

On muddy substrata, the transition from the circalittoral muddy detritic (MD) and terrigenous mud shelf (TMS) biocoenoses to an upper bathyal mud biocoenosis (UBM) remains hypothetical, due to lack of research. However, from the data of Guille (1970), Picard (1971), Salen-Picard (1982), Albertelli, Della Croce and Frascchetti (1991) and Albertelli and Frascchetti (1992), one may argue that there is a faunistic change at the level of the shelf edge, with the appearance of dominant species, particularly the ophiurid *Amphiura filiformis* (Müller, 1776), reaching 8-34 % of the fauna, according to Salen-Picard (1982) and Albertelli, Della Croce and Frascchetti (1991), and the polychaete *Maldane glebifex* Grube, 1860, while the characteristic species from both circalittoral MD and TMS biocoenoses are absent in the upper bathyal. In this hypothetical UBM, some species can reach high densities in some areas, i.e., the echinoderm *Brissopsis lyrifera* Forbes, 1841, the pennatularia *Funicula quadrangularis* (Pallas, 1766) and the sponge *Thenea muricata* (Bowerbank, 1858).

Within the upper bathyal biocoenoses, the faunistic distribution develops into belts related to the prevailing factors (hydrodynamics and the related sedimentary conditions). Consequently, these belts are mainly suspension-feeder ones. The direction and velocity of the bottom currents create five distributional zones in the BDS (the highest velocity zone is reported in figure 1), i.e., the distributional zones of *Gryphus vitreus*, which can reach up to 700 individuals/m² (Emig, 1987, 1989a, 1989b; Emig and Arnaud, 1988; Emig and García-Carrascosa, 1991) or the distribution belt (between 100 to 140-150 m) of the echinoderm *Neolampas rostellata* Agassiz, 1869 reported previously by Falconetti (1980) as belonging to the circalittoral. In the SD, the crinoid *Leptometra phalangium* can reach up to 30-50 individuals/m² (Reyss, 1971) and in the UBM *Amphiura filiformis* reaches up to 28 individuals/m² (Albertelli and Frascchetti, 1992). Such a belt distribution explains the relative heterogeneity of the fauna beyond the shelf-edge, as reported by previous authors, as well as their arguments for considering the upper bathyal a transitional zone.

The upper bathyal biocoenoses seem to be characterised by lower species and individual richness

when compared to the overlying circalittoral biocoenoses; in general, the muddier the substrate, the lower the richness. However, the analysis of recently published data by Albertelli, Della Croce and Frascchetti (1991), Albertelli and Frascchetti (1992) and Tselepidis and Eleftheriou (1992) from muddy shelf-to-upper slope transects show that the macrofauna increases in species and individuals, mainly of suspension-feeders and detritus-feeders, in the upper bathyal zone (figure 3). Within the SD and middle bathyal mud (MBM) biocoenoses on the northern Mediterranean coast, there is a geographic decrease in richness from the west to the east (Carpine, 1970), which needs confirmation because opposite to the cyclonic circulation.

The extension of circalittoral species into the upper bathyal occurs in general down to a depth of 130-140 m, where their presence is probably limited by abiotic factors, i.e., light, pressure or/and hydrodynamics, particularly for polychaetes and echinoderms, while the extension of MBM species into the upper bathyal is limited by the substrate, at least in the SD and BDS. Nevertheless, species which occur at the same time in the circalittoral and bathyal are generally considered as circalittoral species which extend into the bathyal, rarely the contrary. For example, several brachiopod species, i.e., *Megerlia truncata* (Linnaeus, 1767) and *Megathiris detruncata* (Gmelin, 1790), considered respectively as a shallow-water species and an eurybathic species (Logan, 1979), have their maximum density in the upper bathyal, between 100 and 150 m (Emig, 1988).

Phytal-aphytal boundary

This boundary can be estimated by the percentage of the *Gryphus vitreus* shells infested with the green alga *Ostreobium* sp. Bornet and Flahaut. Occurring generally within the upper bathyal zone, its depth varies in relation to the water transparency, i.e., between 180 and 210 m in normal water conditions in Corsica, but it can be restricted to 125-135 m under turbid water conditions (Emig, 1989c). Along the Provençal coast, because only a small number of shells is infested with *Ostreobium* sp., this boundary is estimated at about 150 m depth. Such results indicate that the phytal-aphytal boundary is independent of benthic zonation, and that its depth can fluctuate even within a restricted

geographic area, contradicting Bellan-Santini's (1983) statement that this boundary lies at the lower limit of the circalittoral zone, as well as the definition of the lower limit of the transitional zone proposed by Ercegovic (1957) and Pérès and Picard (1964).

Middle bathyal zone

There is a rapid transition over several tens of meters from the upper bathyal zone to the middle bathyal zone, i.e., from the upper bathyal biocoenoses to the MBM. The substrate becomes muddy, with the appearance of burrowings having various diameters (Emig and Arnaud, 1988; Emig and García-Carrascosa, 1991). Over the continental slope in the middle bathyal, with increasing depth, a general decrease in the size of the macrobenthos is recorded (Carpine, 1970; Pérès, 1985; Sardá and Cartes, 1993; Stefanescu and Cartes, 1992), as well as a quantitative decrease in the macrobenthos (figure 3) and an increase in diversity related to increased environmental stability, associated with increasing depth (Sanders, 1968; Sanders and Hessler, 1969; Haedrich, Rowe and Polloni, 1980; Abelló, Valladares and Castellón, 1988). Nevertheless, four of the five grenadier fish species occurring in the middle bathyal follow the bigger-deeper phenomenon (Massutí, Morales-Nin and Stefanescu, 1995).

There are several faunistic stock changes within the middle bathyal zone, which consequently can be divided into several distributional zones (figure 4), based mainly on recent data from crustacean and fish distribution. However, these zones can be related to several previous proposals, such as that of Pérès (1985), who divided the upper slope into two zones below the transitional one: from 200 to 500 m and from 500 to 1 000 m. Carpine (1970) proposed the following limits: transitional zone, 150-250 m; upper bathyal, 250-550 m; middle bathyal, 550-2 000 m; and lower bathyal, 1 500-3 000 m.

The crustacean assemblages occurring on the upper and on the lower-middle slope correspond to highly differentiated faunistic communities, whose differences can be attributed to hydrological differences. The upper community is associated with the warmer intermediate waters, and the lower zone with the deep-water mass, which has a fairly constant temperature throughout the year

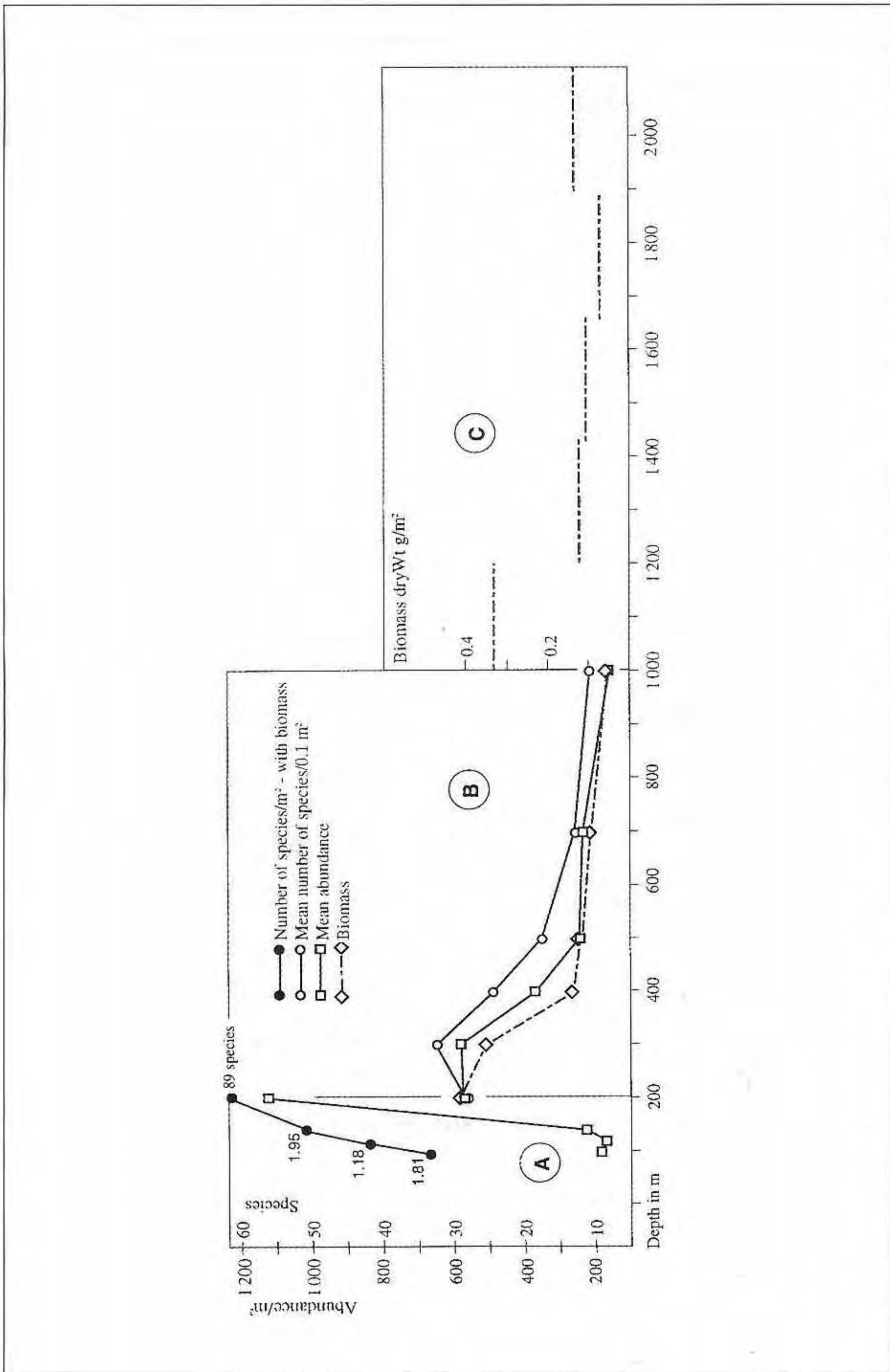


Figure 3. (A): Abundance, species richness and biomass of the macrofauna on the muddy bottoms in the shelf-to-slope sector of the Gulf of Genoa (data from Albertelli, Della Croce and Fraschetti, 1991; Albertelli and Fraschetti, 1992). (B): On a slope transect in the Cretan Sea (Tselepidis and Eleftheriou, 1992). (C): Biomass of demersal fish communities on the slope of Catalonia (data from Stefanescu, Lloris and Rucabado, 1993).

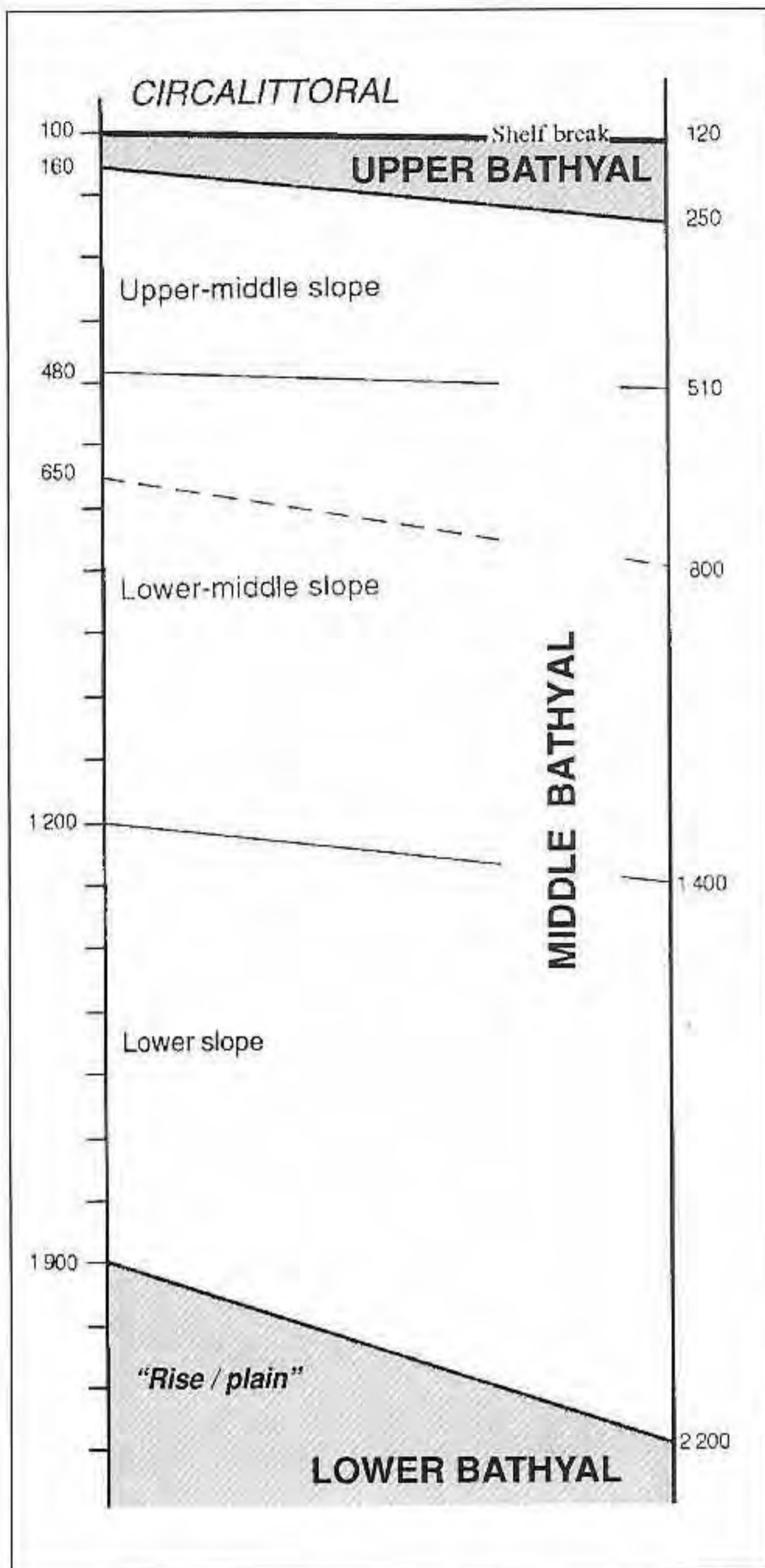


Figure 4. Diagram of bathyal zonation along the Mediterranean continental slope, with the main faunistic changes and boundaries.

(Abelló, Valladares and Castellón, 1988). The greatest abundance of mysids seems to occur on the middle slope (Cartes and Sorbe, 1995). The populations of *Aristeus antennatus* (Risso, 1816) can be divided into seasonal groups on the upper-middle slope, but such groups are less defined in the lower-middle slope, and the seasonal effect becomes very slight on the lower slope (Cartes, 1994).

According to data from Albertelli and Cattaneo (1985) and Albertelli, Della Croce and Frascetti

(1991), on muddy substrates in the Gulf of Genova deposit-feeders represent respectively 63% in the upper bathyal and 37% in the upper-middle slope of the middle bathyal, while suspension-feeders represent respectively 14 and 7%, and predators 20 and 57%. Along a Cretan transect (Tselepidis and Eleftheriou, 1992), polychaete deposit-feeders are dominant between 200-400 m (more than 50%) and carnivores (more than 49%) below 500 m. In the Catalan Sea, the upper-middle slope community (245-485 m) shows a predominance of mesopelagic species (Cartes, Sorbe and Sardá, 1994); the fish assemblage on the lower-middle slope, between 1000 and 1425 m, is dominated by *Lepidion lepidion* (Risso, 1810) with five subdominant species (Stefanescu, Lloris and Rucabado, 1993).

Some authors (Abelló, Valladares and Castellón, 1988; Mura and Cau, 1994) indicate a change in the decapod fauna between 650 and 800 m. According to Sardá and Cartes (1993), the diet of these decapods consists largely of infauna or epifauna, and there are differences in the composition of the diet above and beyond this limit.

On the lower slope, there is evidence of faunistic changes, as well as drastic changes in the amount of available energy and a sharp reduction of the available trophic resources related to the distribution of mesopelagic organisms and hydrological characteristics (Cartes, 1993; Stefanescu, Lloris and Rucabado, 1993; Sardá and Cartes, 1993). The fauna is dominated by demersal fish species with low energy cost, and small epibenthic and bathypelagic invertebrates (Stefanescu, Lloris and Rucabado, 1993). The absence of mesopelagic organisms below 1000-1200 m is reflected by an impoverishment of the benthic ecosystem. Cartes (1993) indicates that one of the most important preys, the decapod *Calocaris macandreae* Bell, 1846, disappears below 1000-1200 m (figure 3). In demersal fish assemblages there is an abrupt decrease in values and a subsequent homogeneity at greater depths (figure 3); the assemblage is dominated by *Bathypterois mediterraneus* Bauchot, 1962, with two subdominant species (Stefanescu, Lloris and Rucabado, 1993).

Canyon valleys

The canyon valleys are subject to specific abiotic conditions, and their macrofauna composition is

too poorly documented to allow comparison (see Monaco *et al.*, 1990; Bourcier, Stora and Gerino, 1993; Gerino *et al.*, 1995). These valleys are geomorphologically important in concentrating and transporting sediment to deeper areas (Monaco *et al.*, 1990), with high dynamic water circulation (Millot, 1990). Their biological importance is due to the input of high productivity with abundant resources, and the occurrence of recruitment areas concentrating juveniles of certain species, particularly in the middle bathyal zone. Fauna biomass and abundance are higher than those recorded on the surrounding slope areas.

DISCUSSION

The zone herein defined as the upper bathyal was previously considered a transitional zone, not only in the Mediterranean but in the World Ocean (see Zenkevitch, 1963; Pérès, 1982; Blake and Doyle, 1983; Zezina, 1994). However, this zone begins at the continental shelf-edge (geomorphological shelf-break) which is characterised by biological, physical and geological expression, and beyond which the upper bathyal develops as a belt whose bathymetric extension is directly related to slope physiography (figure 1). Consequently, future studies of bathyal fauna should always indicate the slope profile from which the data have been reported; this is also valid for the middle bathyal. In the bathyal, the major change in fauna is directly associated with major environmental changes, which play a key role in determination of the fauna across the shelf-break. The biological extension along the slope is given by the biocoenoses occurring in the upper bathyal, dominated by high densities of exclusive suspension-feeders whose distributional belts should provide information regarding flow structures in the shelf-to-slope context.

The validity of the bathyal biocoenoses needs to be established with new data, using faunistic density and biomass and the effects of almost abiotic characters, to define circalittoral and bathyal species and the exclusive species of a biocoenosis, which can only be stenotopic species (Arnaud and Emig, 1987). The distributional zones of fauna determined by abiotic factors need a careful bathymetric and spatial choice of sampling along the slope.

In the Atlantic, infaunal density increases in the uppermost slope zone (Blake and Doyle, 1983).

This also seems to be the case in the Mediterranean upper bathyal, as suggested by the data of Albertelli and Cattaneo (1985), Albertelli, Della Croce and Frascetti (1991), Albertelli and Frascetti (1992) and Tselepidis and Eleftheriou (1992) on muddy bottoms (figure 3). However, the species and individual richness globally decreases from circalittoral to bathyal in the Mediterranean, as also established by Sherman *et al.* (1988) in the northeast Atlantic for the density and biomass of four major taxonomic groups.

The distributional zones in the Mediterranean middle bathyal (figure 4) can be compared with the depth boundary on the Atlantic continental slope at 400, 700 and 1200 m, which are considered nearly universal by Hecker (1990). Nevertheless, this author indicates the following zones: upper slope 180-600 m, upper-middle slope 600-1300 m, lower-middle slope 1400-1600 m, lower slope 1600-2000 m, and a continental rise from about 2000 m.

According to Vanney and Stanley (1983), the shelf-edge appears as a boundary of importance comparable to the coastline, separating the coastal-shelf environment from the deep realms; it is the point where the first major change occurs in the physical gradient, and consequently, in the biological gradient, when entering the deep sea. This upper limit of the deep-sea zone, the bathyal, depending bathymetrically on the depth of the shelf-edge, is expressed by biological, physical and geomorphological criteria which have to coincide with each other and with the lower boundary of the circalittoral zone.

The transition from the upper bathyal to the middle bathyal, whose bathymetric limit depends on local environmental factors governed by physiography, also follows such multidisciplinary criteria. It corresponds in general to the mud line, located between about 165 and 300 m, depending on the slope physiography, in the northwest Mediterranean, where this line also indicates a drastic change in the energy level, as reported in other ocean areas by Stanley, Addy and Behrens (1983).

As a result of steep gradients in physical conditions, the upper bathyal zone represents an underestimated barrier from shelf to deep sea, occurring in the World Ocean. In the Mediterranean, such a physical barrier may partly explain the sharp fauna decrease in the middle bathyal and the biological poverty of the Mediterranean deep sea. On the other hand, along-bottom transport passing

through the canyon axes appear as pathways across the shelf break to the Mediterranean deep sea (Courp and Monaco, 1990).

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