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MEDITERRANEAN-MIDDLE EASTERN ATLANTIC FAÇADE: MOLLUSCAN BIOGEOGRAPHY & ECOBIOSTRATIGRAPHY THROUGHOUT THE LATE NEOGENE

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ABSTRACT

We propose the definition of Atlantic pre-glacial Pliocene Molluscan Units and a critical comparison with the Mediterranean Pliocene Molluscan Units (MPMU1) of Raffi & Monegatti (1993). Our aim is to outline the extent and boundaries of the pre-glacial climatic zone (in the sense of Hall, 1964) by means of molluscan proxy data. This approach enables to demonstrate that the latitudes between 38° and 40° both through the pre-glacial Pliocene, before 3.0 Ma, and at the Present-day, mark the transition between two different climatic marine zones. These latitudes marked the boundary between the tropical and subtropical zones in the pre-glacial Pliocene, whereas they correspond to the subtropical-warm temperate transition in the Present-day. A similar pattern is recognizable at about Latitude 50° North which in the present-day approximates the boundary between the warm-cool temperate climatic zones and in the pre-glacial Pliocene marked the boundary between the subtropical-warm temperate zones. This setting has been linked to the long-standing debate on marine latitudinal diversity gradients and their explanations. Productivity as a consequence of temperature regime triggered by solar input and geographic-oceanographic setting appear to be the basic factors (Roy *et al.*, 1998).

INTRODUCTION

The Zanclean-Early Piacenzian is unanimously defined as the last warm age before the onset of the glacial climatic age. As matter of fact this age is a stable warm time interval between the warmer Late Tortonian-Early Messinian age, when tropical fauna (Monegatti & Raffi, 2001) thrived at the latitudes of 48°-50° North in North Western France, and the onset of the Glacial age at about 3-2.9 Ma. This warm time interval is characterized, in the Mediterranean Basin, by a tropical marine molluscan fauna categorized as Mediterranean Pliocene Molluscan Unit 1 (MPMU1 of Raffi & Monegatti, 1993, and Monegatti & Raffi, 2001).

The Pliocene marine mollusc record along the European Coast is scanty, discontinuous and often difficult to date. Despite these difficulties molluscan record provides a good opportunity to depict the biogeographic scenario of the pre-glacial Pliocene. Our approach will be the comparative analysis of the Mediterranean MPMU1 with the coeval molluscan fauna of South Western Andalusia, Portugal, North Western France and the Southern North Sea Basin.

Our main purpose is to suggest the definition of molluscan biogeographic units and to outline the extent and the boundaries of the preglacial Pliocene climatic zones.

The present-day marine climatic zone boundaries along the Southern European coast

Since Hutchins (1947) and Hall (1964), the biogeographic molluscan units and the shallow water marine climatic zones are known to be closely linked. Northwards along the European Atlantic Coast the boundaries between the biogeographic units (and the relative climatic zones) are essentially defined by the North end range of a significant stock of taxa and by an evident decrease in the latitudinal gradients of taxonomic diversity.

About 40 shallow water bivalve species (Raffi *et al.*, 1989) and a much higher number of gastropod taxa, including the Fasciolaridae, Mitridae and Cancellaridae (Taylor & Taylor, 1977), do not extend their distribution beyond 38°-40° Lat North. The North end range of this stock of taxa defines the transition between the Mediterranean-Moroccan/Iberian-French molluscan biogeographic unit which corresponds to the subtropical-warm temperate climatic zone transition of Hall (1964). At 49°-50° the North end range of at least 20 species of bivalves and at about 25 species of gastropods (data from Seawards, 1990, 1993) defines the transition between the French-Iberian and the Celtic biogeographic unit which corresponds to the warm-temperate-mild temperate climatic zone transition (Hall, 1964).

Mediterranean Pliocene events and the definition of Mediterranean molluscan units

Throughout the Mediterranean Pliocene the extinction phases of the molluscan fauna offer an easy means of monitoring the Northern Hemisphere transition from a preglacial to a glacial regime and the main biogeographic-paleoclimatic changes.

Taking into consideration the Pliocene extinction events and the Mio-Pliocene and Plio-Pleistocene faunistic changes, Raffi & Monegatti (1993) have defined four Mediterranean Pliocene Molluscan Units (MPMUs), each delimited by two extinction events (Fig. 1). We refer to Monegatti & Raffi (2001) for an analysis of the bivalve richness of every unit. Each unit marks a particular time interval in the climatic oceanographic evolution of the Mediterranean ecosystem, which is clearly related to the climatic changes of the Northern Hemisphere. Thanks to new stratigraphic data (Monegatti *et al.*, 2001, 2002) the dating of the MPMUs has been emended as quoted in Fig. 1. As a matter of fact Terebridae and *Flabellibepecten* disappearances have been respectively correlated with the 110 and 100 marine isotopic stages (Monegatti *et al.*, 2002). We suggest that the definition of Pliocene molluscan units along the Eastern Atlantic Coast, their dating and com-

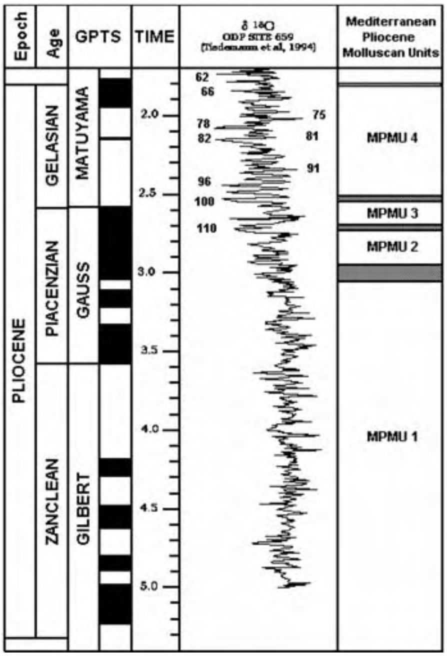

FIGURE 1. Mediterranean Pliocene Molluscan Units (MPMU) of Monegatti & Raffi (2001) ememded with the new stratigraphic data of Monegatti *et al*. (2001) and Monegatti *et al*. (2002).

parative analysis could promote the understanding of the climatic biogeographic changes, the aim being the triggering of a cognitive domino effect.

Preglacial Late Neogene biogeography along the European coast

Mediterranean, Atlantic Andalusia and Portugal

The starting point for unravelling the biogeographic significance of the Early Pliocene Mediterranean and Atlantic mollusc fauna is based on three main steps: a) the definition of MPMUs (Mediterranean Pliocene Mollusc Units) and the admission of the tropical significance of the MPMU1 in the sense of Hall (1964) slightly modified by Raffi *et al*. (1989); b) the stratigraphic evidence that MPMU1 time includes both the Pliocene of Huelva and of Vale do Freixo (Sierro *et al*., 1990; Silva, 2001, 2003); c) the hypothesis that, at least in the Early Pliocene, Southern Portugal represented the Northern boundary of a tropical province which in Miocene was extended up to the North France (Monegatti & Raffi, 2001; Silva, 2001, 2003).

The MPMU1 refer strictly to the Mediterranean and is not applicable

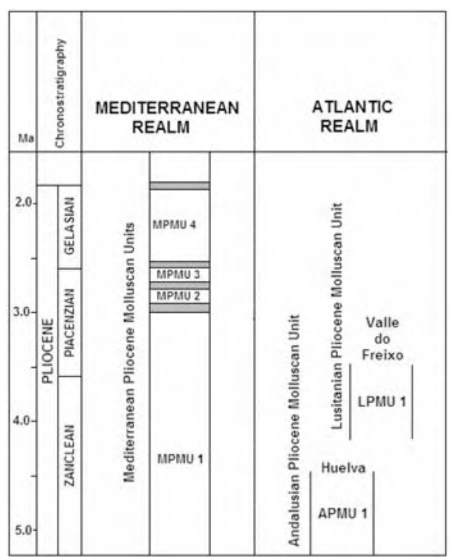

FIGURE 2 – Stratigraphic setting of Early Pliocene Molluscan Atlantic Units: the Lusitanian Pliocene Mollusc Unit 1 (LPMU1) and the Andalusian Pliocene Mollusc Unit 1 (APMU1).

to the Atlantic Realm; therefore we propose to introduce two Molluscan Atlantic Units, the Lusitanian Pliocene Mollusc Unit 1 (LPMU1) and the Atlantic Andalusian Pliocene Mollusc Unit 1 (AAPMU) (Fig. 2). We refer here to the works of Silva (2001, 2003 with references) and Gonzales Delgado *et al*. (1984, with references); these units and their features will be the object of a joint paper.

The interpretation of the malacofauna of Pombal (Portugal) as a record of the tropical-subtropical transition is based on two points:

a) the presence of a few taxa typical of MPMU1 such as *Callista italica* (Defrance), *Distorsio tortuosa* (Borson), *Paphia vetula* (Basterot), *Palliolum excisum* (Bronn) in the context of subtropical fauna; b) the evidence that some of the still living tropical taxa (e.g. *Circomphalus foliaceolamellosus* (Dilwyn), *Strioterebrum reticulare* (Pecchioli in Sacco) etc.) are typical both of the Early Pliocene and

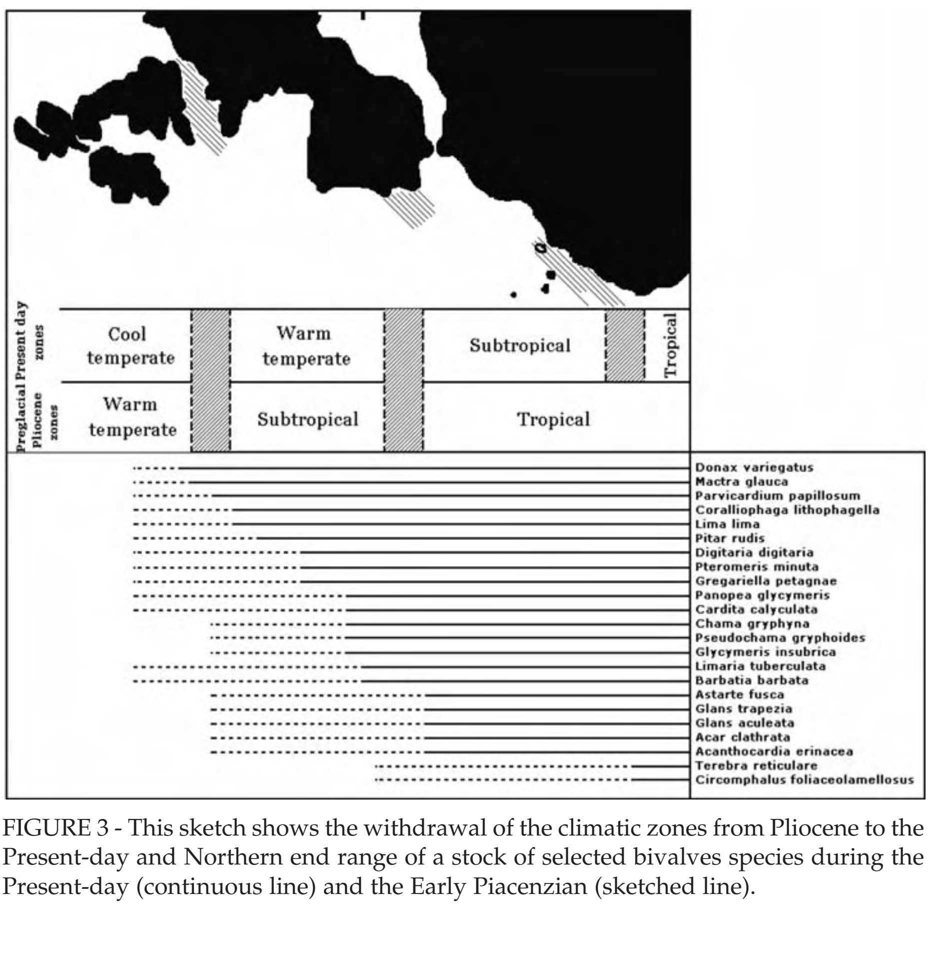

FIGURE 3 - This sketch shows the withdrawal of the climatic zones from Pliocene to the Present-day and Northern end range of a stock of selected bivalves species during the Present-day (continuous line) and the Early Piacenzian (sketched line).

present-day tropical-subtropical transition respectively along the Portugal coast, at 38°-40° lat. North, and along the West African coast (Cape Blanc-Cape Barbas) at 20°-22° lat. North (see also Silva, 2001, 2003) (Fig. 3).

The most interesting achievement is that the present-day subtropical-warm temperate transition approximates the latitude of the tropical-subtropical transition throughout the Zanclean and Early Piacenzian (Monegatti & Raffi, 2001; Silva, 2001, 2003).

If that is the case, following a domino effect, there would have been an unknown subtropical bioprovince North of Portugal. In such a scenario the debate on the age and significance of the Redonian appears of outstanding importance.

<u>The Redonian: a window on the Late Miocene tropical-subtropical change</u>

The recent Strontium isotopic data on mollusc shells of Redonian of Mercier *et al*. (2000) and Neraudeau *et al*. (2002, 2003) have come up again the old debate on the age of the Redonian local stage of Dollfuss (1901). These isotopic data performed on molluscan shells reconfirm the ecobiostratigraphic framework of the malacologists (Brebion, 1964; Lauriat-Rage, 1981) based on the distinction between a Redonian **1** (or warm Redonian) and a Redonian **2** (or cool Redonian). The Redonian **1** has been dated at about 7-6.5 and 6.5-6 Ma and the Redonian **2** at 7-6 and 6.0-4.6 Ma respectively in the Anjou Region and in the "Redonien stratotypique". Briefly the age of the Redonian would be essentially Messinian, without ruling out a Late Tortonian or Early Pliocene age.

The dating of Redonian **1** fully reconfirm the stratigraphic interpretation of Brebion (1964; in Lauriat-Rage *et al*., 1989a) who interpret this unit as late Miocene. Forty years later we fully agree with Brebion (1964) who emphasized that the Redonian **1** shows a stronger faunistic affinity with "the faluns Helvetien de Touraine" than with the Redonian **2**.

We refer to Brebion (1964) for a detailed analysis of his Miocene gastropods fauna.

Lauriat-Rage (1981) interpreted the bivalve fauna of Redonian **1** (Reneauleau, Sceaux, etc.) as Early Pliocene but her bivalve list too (which include *Anadara turonica* (Dujardin), *Barbatia vincenti* (Couffon), *Cardites subaffinis* (Tournouer), *Cardites monilifera* (Dujardin), *Cardites crassa* (Lamarck), *Venus fallax* Millet, *Venus subrotunda* Defrance and possibly *Nemocardium spondiloydes* (Von Hauer), *Manupecten fasciculata* (Millet), *M. puymoriae* (Mayer), etc.) supports a reference to the Late Miocene.

The presence of *Hinnites crispus* (Brocchi), *Spondylus crassicosta* Lamarck, *Trachycardium multicostatum* (Brocchi), *Spisula proaspersa* (Sacco), *Callista italica* (Defrance), *Corbula carinata* (Dujardin), *Corbula revoluta* (Brocchi), *Corbula cocconii* Fontannes, and among the gastropds, *Conus dujardini* Deshayes, *C. mercati* Brocchi, *C. antiquus* Lamarck, *Terebra acuminata* Borson, which characterize the Mediterranean

Early Pliocene (MPMU1), and *Hastula subcinerea* (D'Orbigny), supports the evidence of a tropical environment at least up to 48° Lat North (Fig. 3).

The Redonian **2** unit is characterized by a strong faunistic impoverishment but the extant Miocene taxa, following the molluscan lists of Brebion (1964), Brebion and Lauriat-Rage (in Ters *et al.*, 1970; Lauriat-Rage *et al.*, 1989b), suggest again a reference to a Late Miocene. The faunal composition of "La Limouzinière for … «longtemps servi de gisement de reference pour le Pliocene à facies Redonien» (Dudicourt *et al.*, 2005) allows to focalize the main characters of the Redonian **2** faunal composition (Lauriat-Rage *et al.*, 1989b). In fact, the survival of typical Miocene taxa such as *Anadara turonica* (Dujardin), *Barbatia vincenti* (Couffon), *Natica neglecta* Mayer, *Cerithiopsis vignali* Cossman & Peyrot, *Clanculus baccatus* (Defrance), *Mitraria gravis* Bellardi, *Circulus planorbillus* (Dujardin), etc., suggests again a reference to a faunal (even if impoverished) Late Miocene composition. It is also of particular interest the appearance of new taxa such as *Cirsotrema funiculus* (Wood), *Cirsotrema fimbriosum* (Wood), *Epitonium frondiculum* (Wood), *E. subulatum* (Sowerby), *Turbonilla internodula* (Wood), and others which were not cited in the Redonian **1**. These new appearances and the decrease in Miocene taxa show a strong analogy with the Mediterranean faunal change throughout the Late Tortonian-Messinian, before the salinity crisis.

Furthermore, among the rich contingent of tropical species of the Redonian **1** only two species are still present, *Hinnites crispus* (Brocchi), and likely *Venus excentrica* Agassiz (in our opinion cited as *Venus subrotunda* in Lauriat-Rage, 1989b, tav. VII, fig. 6). Taking into consideration also the sites of Vendée (in particular Palluau) we can add *Calliostoma tauromiliare* Sacco (which survive in the Early Pliocene of Estepona) and *Chicoreus bourgeoisi* (Tournouer) a present-day species of West Africa.

Among the warm water taxa, the extant subtropical taxa represent the more numerous group: *Calliostoma conulum* (Linné), *Serpulorbis arenarius* (Linné), *Seila trilineata* (Philippi), *Clathrella clathrata* (Philippi), *Muricopsis cristata* (Brocchi), *Typhinellus sowerbyi* (Broderip), *Glans aculeata* (Poli), *G. trapezia* (Linné), *Acanthocardia erinacea* (Lamarck), *Acar clathrata* (Defrance), *Astarte fusca* (Poli), which do not extend North of 37°-38°, and other species such as *Panopea glycymeris* (Born), *Glycymeris insubrica* (Brocchi), *Barbatia barbata* (Linné), *Chama gryphoides* (Linné), *Pseudochama gryphina* (Linné), *Cardita calyculata* (Linné), which do not spread North of Portugal or Northern Spain and therefore mark the transition between the subtropical and warm-temperate zone (Hall, 1964) (Fig. 3). Also of particular interest is the presence of some Mediterranean Pliocene taxa such as, *Limopsis aradasi* (Testa) (cited as *L. recisa* Defrance), *Parvicardium hirsutum* (Bronn), *Clausinella scalaris* (Bronn), *Clavagella brocchii* (Lamarck), *Clavagella bacillum* (Brocchi), *Ficus geometra* (Borson), *Narona tauroparva* (Sacco), etc., which thrived in the Mediterranean and disappeared throughout the Late Pliocene or the Early Pleistocene.

Eventually, the molluscan fauna of the Redonian **2** appears typical of a subtropical climatic zone, still characterized by few taxa with tropical affinity.

Our conclusions are that a) the faunistic change between Redonian **1** and Redonian **2** correspond to the transition from a tropical to a subtropical climatic zone; b) this change dates back to the Messinian.

The age of the classical site of Goubersville is still matter of debate, even if interpreted as Pliocene by both Brebion (1964) and Lauriat-Rage (1981). No tropical taxon is cited in this site and the only warm-water taxa are represented by some of the subtropical taxa recorded in the Vendèe Region (*Serpulorbis arenarius* (Linné), *Seila trilineata* (Philippi), *Barbatia barbata* (Linné), (?) *Manupecten pesfelis* (Linné), *Acar clathrata* (Defrance), *Lima lima* (Linné), *Pseudochama gryphina* (Lamarck), *Cardita calyculata* (Linné)) and others warm-temperate species such as *Digitaria digitaria* (Linné) and *Irus irus* (Linné). The low number of subtropical taxa and the presence of *Modiolus modiolus* (Linné) suggest a reference to a subtropical zone, likely just to the transition with a northern warm-temperate zone.

This interpretation is based on the low number of subtropical taxa and the presence of *Modiolus modiolus*, a boreal species which today extends its southern distribution southwards to the Biscay Gulf.

A Late Messinian-Early Pliocene faunal composition appears as the most appropriate definition for the molluscan association of Goubersville.

Finally, we hypothesise that since at least the Late Messinian, a subtropical bioprovince extended from the latitude 38°-39° North up to about 49°-50° North, approximately with the same range of the present-day warm temperate zone (Fig. 3).

Such an interpretation fully matches the data of Dowsett *et al*. (1999, 2005) who suggested a mean Pliocene August SST of 22°C at the latitudes of the northern Normandy. The analysis of the Anglo-Belgian-Dutch Early Pliocene is of basic importance in order to test this hypothesis.

<u>The Southern North Sea Basin</u>

The correlation of the Pliocene deposits in the Southern North Sea Basin (S.N.S.B.) has always been difficult because the shallow water sedimentary record is discontinuous, highly incomplete and lacking in planktonic markers such as calcareous foraminifera and nannoplankton. Despite recent progress in the stratigraphy of this basin, we shall limit ourselves to the mollusc fauna of the Early Pliocene formations, until a more stable and objective time framework is obtained.

According to Louwye *et al*. (2004) dinoflagellate cysts from the Kattendijk Formation are indicative of an Early Zanclean age, presumably between about 5.0 and 4.7-4.4 Ma; furthermore the overlying Lillo Formation (whose base is constituted by the Lutchball Sands Member) is interpreted as "Late Zanclean-Early Piacenzian" in age and the unconformity at its base has been "correlated with the sequence boundary Za2 at 4.04 Ma or Pia1 at 3.21" of Hardenbol *et al*. (1998). Following the same authors, the dinoflagellate cysts indicate a conspicuous climatic cooling at the very base of the Lillo Formation. As a matter of fact, bivalve record does not show any important taxonomic richness change between the Kattendjik formation and the overlying Lutchball Sands (Marquet, 2002, 2005) and we interpret its fauna as belonging to the same ecobiostratigraphic-biogeographic unit (Fig. 4).

Furthermore, according to Head & Norris (2003) the finding of the acritarch *Leiospheridia rockhallensis* in the Ramsholt Member, supports an Early Pliocene age, between 4.4 and 3.9 Ma for the Coralline Crag. This new dating is slightly older than the previous interpretation which located the Coralline Crag in the Gilbert chrone between the Cochiti subchrone and the Gilbert/Gauss boundary (Hodgson & Funnel, 1987; Funnel, 1996).

Considering that the molluscan fauna of the Kattendjik Formation, Lutchball Sands, and Coralline Crag do not show tangible differences, they belong to the same basin and are

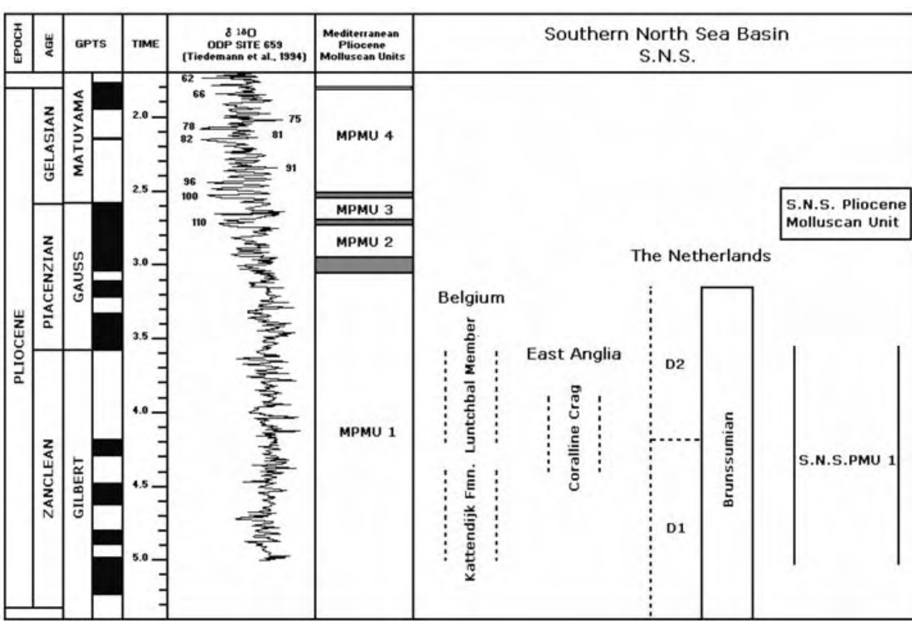

FIGURE 4 - Stratigraphic setting of the Early Pliocene Molluscan unit of the Southern North Sea Basin (S.N.S.PMU1)

all included in the Brunssumian (Andrew & West, 1977; Meijer, 1993; etc.), we interpret them as a unique ecobiostratigraphic-biogeographic unit (Fig. 4).

On the whole, this SNS Mollusc Pliocene Unit (SNSMPU1) which ought include also the D2 and D1 units of Spaink, (1975) (Meijer, 1993) is characterized both by still living taxa over a wide latitudinal range and numerous North Sea endemic taxa, probably as a consequence of the Dover Street Closure up to the Early Pliocene. The interpretation of these taxa as climatic markers is problematic and would require a careful analysis of their origin. Some of the extant taxa have, however, an apparent climatic significance. *Limaria tuberculata* (Olivi), *Barbatia barbata* (Linné), *Lima lima* (Linné), *Chama gryphoides* (Linné), *Panopea glycymeris* (Born), are present-day species typical of the subtropical zone which are cited up to 40°-41° North in the southernmost warm temperate zone. *Pitar rudis* (Poli), *Digitaria digitaria* (Linné), *Gregariella petagnae* (Scacchi), and *Pteromeris minuta* (Scacchi), do not cross northwards the Latitude of 44°-46° (Fig. 3). Other species such as *Coralliophaga lithophagella* (Lamarck), *Donax variegatus* (Gmelin), *Papillicardium papillosum* (Poli), and *Mactra glauca* Born, do not spread beyond approximately 50° North (Fig. 3).

The presence of *Arctica islandica* (Linné), *Mya truncata* Linné, *Macoma obliqua* (Sowerby), and many endemic taxa of the North Sea (Marquet, 2002, 2005) allows a clear cut biogeographic distinction from the "Early Pliocene" of Vendée. The presence of present-day warm temperate species and of a few taxa, typical of the subtropical - warm temperate zone transition, enables us to locate this biogeographic unit in a warm climatic zone, in the sense of Hall (1964). This interpretation is fully consistent with the presence of a Pliocene subtropical bioprovince just south of the Anglo-Belgian-Dutch Basin.

We refer to the works of Marquet (2002, 2005) for an up to date analysis of the Belgium Pliocene bivalve fauna.

CONCLUSIONS

We hypothesize that it was throughout the Late Messinian age that the tropical-subtropical transition withdrew from Northern France southwards to the Portugal latitudes (Monegatti & Raffi, 2001).

Whether this new setting is due to a threshold effect, or to major climatic oceanographic changes, is beyond the scope of this paper. At least as far as molluscan fauna is concerned, this biogeographic setting remained stable up to about 3 Ma (Monegatti & Raffi, 2001) and then finally, starting from 2.7-2.6 Ma, it underwent modification to the present-day conditions. Thanks to one of the referees of our work, we learned that our conclusions are similar to those of Silva & Landau (2007), on the gastropods. The analysis of the differences between our data and those of Silva and Landau will be the object of another work (Monegatti & Raffi, in progress), because this paper was submitted to *Açoreana* before the printing of Silva and Landau's work.

The new interpretation of the Redonian on the part of the French school (Neraudeau *et al*., 2003, with references) has opened new interesting perspectives on our knowledge of the Messinian age. The pattern of extinction and the withdrawal of the tropical taxa southward, suggest the hypothesis that the "Pliocene biodiversity" had already been acquired, both at the latitudes of Gibraltar and North-Western France, at least since 5.5 Ma (0.2 my before the conventional Miocene-Pliocene boundary), that is, at the end of the Messinian glaciations (Shackleton *et al*., 1995) (work in progress).

The work of Marquet (2002, 2005), on the mollusc fauna of the Belgium Pliocene, provides us with sufficient evidence to state, on a steady taxonomic basis, that latitudinal diversity gradients had already been very steep at least since the Early Pliocene. In fact, Marquet (2002, 2005) cites 185 bivalve species for the Belgium Pliocene (highly representative of the SNSB biodiversity) and at least 355 shallow water species have been listed for the Mediterranean Pliocene (Monegatti & Raffi, 2001). Moreover, if we also consider the specimens still waiting to be described on the desks of Pliocene malacologists, 400 would be a more realistic number (see also Marasti & Raffi, 1980 for a list of taxa to be checked). This strong gradient is in tune with the expected differences between a tropical and warm temperate bioprovince. In all probability, the latitudinal biodiversity gradients increased progressively throughout the Late Miocene, and decreased again from about 3.0 Ma with the onset of the Earth's climatic cooling.

Climatic-oceanographic changes always determine new seasonal temperature patterns, which control the biodiversity of the climatic zones, and give origin to new unpredictable biota (Monegatti & Raffi, 2001). Historical and geographical factors, upwelling conditions, and spatial heterogeneity play a further fundamental role. The best strategy to unravel the biogeographic Mio-Pliocene history of the European Eastern Atlantic is to define and compare well dated ecobiostratigraphic-biogeographic units from different regions.

The southward shifting of the climatic zones throughout the Late Messinian to the Present-day setting is not surprising and due, clearly, to the Earth's climatic cooling (Fig. 3). What is unforeseeable, however, is the stability of the oceanographic thresholds at about 38°-40° and 48°-50° Lat North.

The interplay of the regional oceanographic pattern and the latitudinal solar energy input appears to be the general factor controlling the boundaries between climatic zones. A possible hypothesis is that the Late Neogene stability of the thresholds along the European coast is due to the prevailing imprinting of the latitudinal pattern of solar energy. Data and interpretation need to be integrated with more copious data, but without doubt the southern displacement of the climatic zones and the stability of the climatic thresholds throughout the Late Neogene poses a stimulating problem to be analysed and critically verified on a global scale.

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