



Middle Miocene foraminifera from Canals (Valencia, western Mediterranean). Biostratigraphic and palaeoenvironmental aspects

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ABSTRACT

The age and the palaeoenvironmental conditions of the *tap* marls outcroppings near the locality of Canals in the south of the Valencia Province (E Spain) are discussed. Based on the planktonic foraminifera assemblages, mainly the species *Globorotalia praemenardii*, these *tap* marls are dated as Serravallian in age (middle Miocene). The analysis of the foraminiferal assemblages suggests a relatively well-ventilated upper-middle bathyal environment, with only a moderate oxygen deficiency throughout most of the studied section. The rather cool waters indicated by the planktonic foraminifera (e.g. *Globigerina bulloides*) are compatible with the decreasing temperatures trend during the middle Miocene due to the extension of the Antarctic Ice Cap. The abundant diatoms and radiolaria, and the highly diverse benthic foraminiferal assemblages are also consistent with prevailing upwelling conditions and a high surface productivity and carbon flux. The apparent warming trend throughout the short section analysed, together with the sharp decrease in diversity and the rise of dysoxic species like *Globobulimina affinis* at the uppermost sample, might indicate either a short-term warming episode or a restriction of upwelling currents,

RESUMEN

Se discuten la edad y las condiciones paleoambientales en que se depositaron las margas *tap* que afloran cerca de la localidad de Canals al sur de la provincia de Valencia (E España). A partir de las asociaciones de foraminíferos planctónicos, sobre todo de la presencia de la especie *Globorotalia praemenardii*, se propone para ellas una edad Serravalense (Mioceno medio). El análisis de las asociaciones de foraminíferos sugiere un ambiente batial superior-medio, relativamente bien ventilado y con sólo una moderada deficiencia de oxígeno a lo largo de la sección estudiada. Las aguas más bien frías indicadas por las asociaciones de foraminíferos planctónicos (como *Globigerina bulloides*) son compatibles con la tendencia al descenso térmico que se produjo en el Mioceno medio debido a la extensión del casquete polar antártico. La abundancia de diatomeas y radiolarios y la alta diversidad de las asociaciones de foraminíferos bentónicos también son coherentes con el predominio de condiciones de *upwelling* y una alta productividad superficial. La aparente tendencia al calentamiento a lo largo de la corta sección estudiada junto con el marcado descenso en diversidad y el incremento de especies disóxicas como *Globobulimina affinis* en la muestra

eventually resulting in more sluggish bottom circulation and less well-oxygenated waters.

Keywords: Foraminifera, middle Miocene, biostratigraphy, palaeoenvironment, Valencia, Spain.

superior podrían estar señalando un episodio de calentamiento a corto plazo o la restricción de las corrientes de *upwelling*, lo que daría lugar a una circulación de fondo más lenta y a ambientes peor oxigenados.

Palabras clave: Foraminíferos, Mioceno medio, bioestratigrafía, paleoambiente, Valencia, España.

1. INTRODUCTION

The geological aspects of the marine Miocene deposits of the Valencia Province (Valencian Community, Eastern Spain) have been specifically studied by several authors (Guignoux & Fallot, 1926; Darder, 1929, 1945; Brinkmann, 1931), although they have been also included in more general surveys (IGME, 1976; Gutiérrez *et al.*, 1984). In particular, the Miocene foraminifera from the Province of Valencia were first studied by Colom (1936); later Usera (1972, 1973, 1974a, 1974b, 1975) and Calvo Sorando *et al.* (1974) carried out more detailed analyses on palaeogeographic, taxonomic and biostratigraphic aspects of several local Miocene outcrops in the Valencia province, based on fossil foraminifera. Later on, Gebhardt (1994, 1999) extensively analysed the foraminiferal assemblages recovered in many sections from middle and upper Miocene marl beds in the Province of Alicante, including the palaeoecological conditions (oxygenation levels) and the palaeoceanographic fluctuations that existed during that time interval. More recently, a series of detailed works (Corbí, 2010, 2017; Corbí *et al.*, 2010, 2016; Corbí & Soria, 2016), partly based on planktonic foraminifera, have described the geology, biostratigraphy, palaeogeography and palaeoenvironmental conditions of the Bajo Segura Basin, also in the province of Alicante, although they are mainly focused on the upper Miocene and Pliocene.

The middle Miocene series in the south of the Valencia Province starts with a deposit of conglomerate and sandstones that unconformably lie on Mesozoic materials. They are followed by sandy marls, which display at their uppermost part a thick bed of white or bluish marls locally known as *tap*. The top of this bed is eroded and covered mostly by Tertiary continental marls and clays and, in some places, by Quaternary travertine limestones.

The age of these marls has been variously attributed either to the middle or to the upper Miocene (IGME, 1975, 1976). Therefore a more detailed sampling of some of the Miocene outcrops seems necessary. This work presents the results of the study of one of these marine *tap* marls sections, near the locality of Canals (South of the Valencia Province).

The main goal of the present work is to determine more precisely the age of the studied section basing on its content in planktonic foraminifera. Additionally, different palaeoenvironmental characteristics, such as

palaeobathymetry, temperature variation and oxygenation levels, were estimated from the analysis of the foraminiferal assemblages. This work is intended to serve as a starting basis for further research on both the detailed chronology and palaeoenvironmental significance of the Miocene sediments in the south of the province of Valencia.

2. MATERIAL AND METHODS

A total of 13 samples (>50g) were recovered from a section located in the district of Canals (coordinates: 38°57'13''N and 0°37'50.23''W), next to the A-35 freeway, between the localities of Moixent and Montesa (Figs 1a–1c) in the south of the Valencia Province. The section is composed by homogeneous whitish silty marls with no discernable facies change (Figs 1d-1f). Samples were extracted at 20–30 cm intervals along a 2.50 m profile, subdivided in two subsections 3.65 m apart to avoid covered and vegetated areas (Figs. 1e-1f), and included in plastic bags. In the laboratory they were weighted and left for 48 h in a hot water solution of 3% hydrogen peroxide (H_2O_2) and 6% sodium hydroxide (NaOH) in order to better disaggregate the sediments. Subsequently, the samples were washed over 250, 125 and 63 μ m mesh sieves, dried under hot lamps and dry-weighted. The >125 μ m fraction was used for this study.

Samples contained abundant foraminifera and were also rich in diatoms, radiolarians and sponge spicules. In each sample at least 300 foraminiferal tests were picked, identified, counted and fixed in micropalaeontological slides. The taxonomic identification of the foraminifera was mainly based on Saavedra (1961), AGIP (1982), Kennett & Srinivasan (1983), Papp & Schmid (1985) and BouDagher-Fadel (2015) together with the website database of Hayward *et al.* (2017). The most representative species are shown in Figures 2-4.

The alpha diversity index α (or Fisher's alpha index) was calculated for the benthic foraminiferal assemblages in each sample. This index is based on the observation that many faunal distributions fit the logarithmic series (Fisher *et al.*, 1943), which is fixed by two variables: the number of species S and the number of individuals N , related by the formula $S = \alpha \ln(1 + N/\alpha)$. The alpha index α cannot

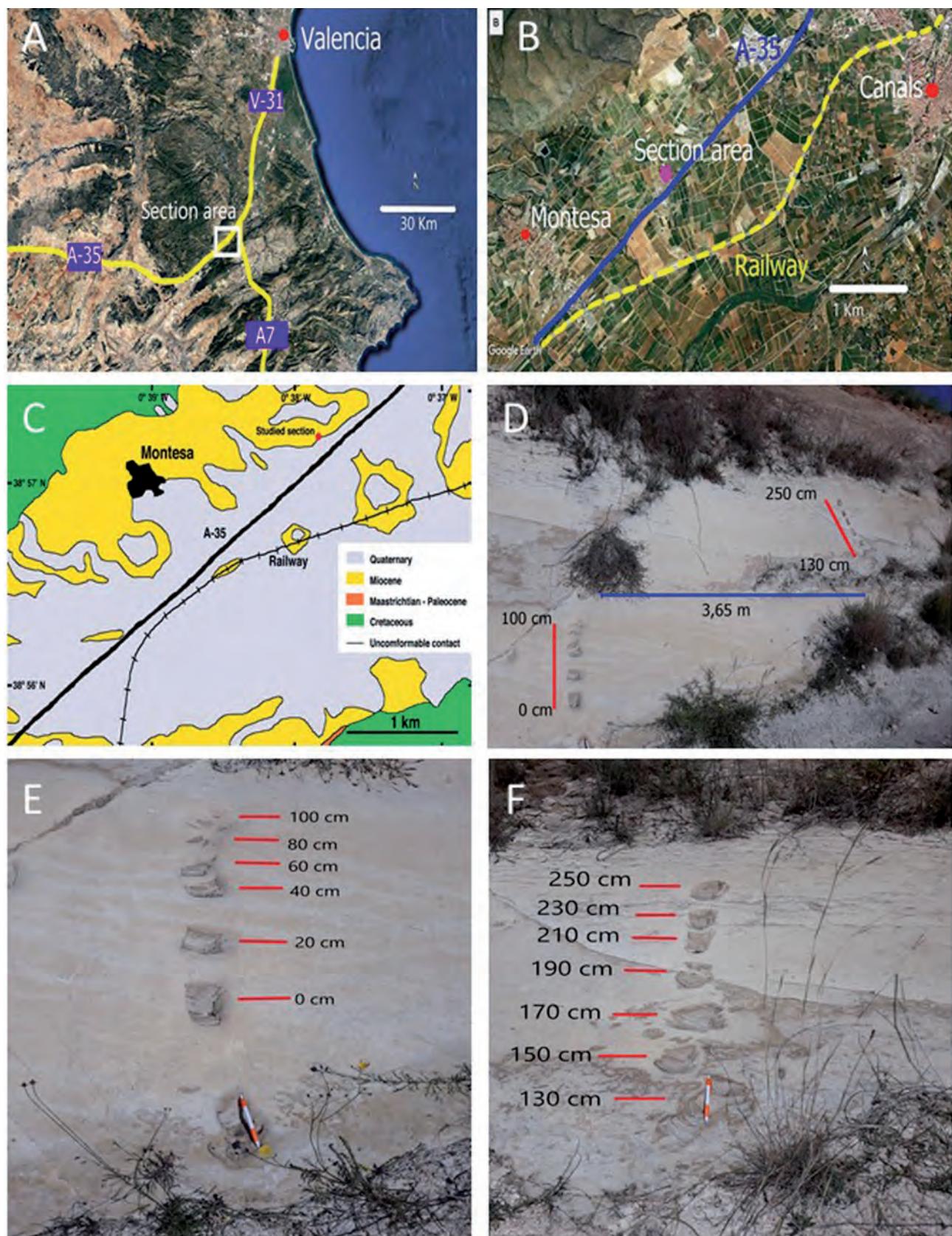
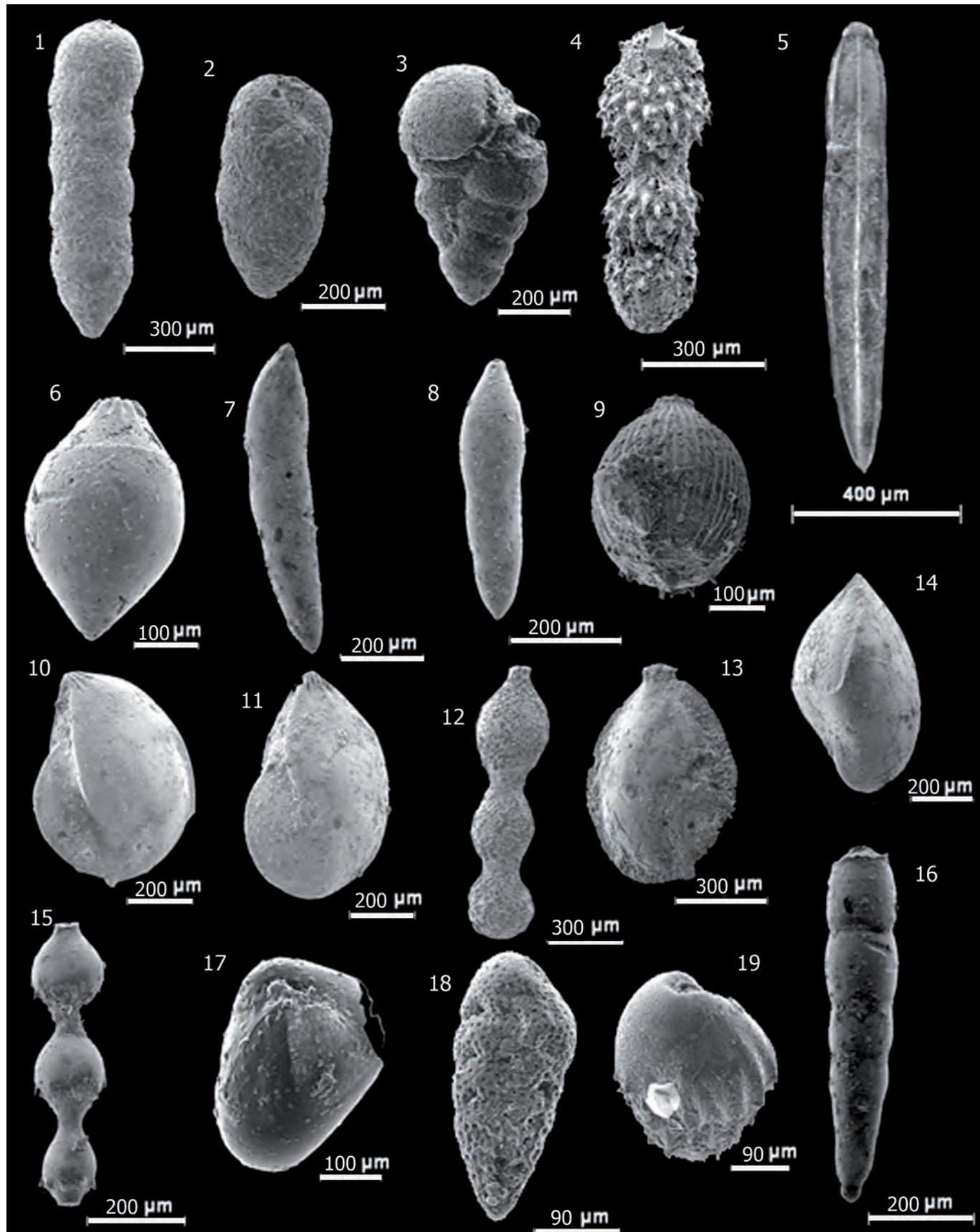


Figure 1. **a)** Google Earth view showing the geographic situation of the studied section in the Iberian Peninsula, western Mediterranean (coordinates: 38°57'13"N and 0°37'50.23"W). **b)** Google Earth view of the Canals-Montesa area with the location of the studied section. **c)** Geologic scheme of the area and location of the studied section (redrawn and simplified from IGME, 1976). **d)** Studied profile showing the two sampled subsections. **e)** Sampling points along the lower subsection. **f)** Sampling points along the upper subsection.



be algebraically calculated and specific software or tables are commonly used instead. Here we have employed the Appendix Table 4 of Hayek & Buzas (1997). Although in three of the samples (at 60, 150 and 170 cm) only 50–100 benthonic foraminifera were recovered, they still were included in the calculations for comparison purposes. The Shannon-Wiener diversity index H' was also calculated, from the formula $H' = -\sum p_i \ln p_i$, where p_i is the proportion of the i^{th} foraminiferal species in the benthonic assemblage. This index has been here expressed as $N_1 = e^{H'}$ (where e is the natural logarithm base) since 1) it can be more clearly interpreted as the number of equally common species that would correspond to an assemblage with diversity H' (Hill, 1973, see also Jost, 2006) and 2) it yields values similar in range to the Fisher alpha index, thus facilitating the inclusion of both curves in a single figure.

The P:B ratio is here expressed as the percentage of planktonic tests: $\%P = 100*P/(P+B)$ where P and B are respectively the number of planktonic and benthonic foraminifera. This ratio was then employed to carry out palaeobathymetric estimations using the regression provided by De Rijk *et al.* (1999) and based on data from the recent western Mediterranean: $\%P = 21.1 \cdot \ln(x) - 64.1$, where x is the estimated depth (in m). An alternative expression proposed by Van der Zwaan *et al.* (1990) was also calculated according to the equation: $x = e^{3.58718 + 0.03534 * \%P}$, where x is the estimated depth, e is the base of the natural logarithm, and $\%P' = 100*P/(P+B-S)$, where S denotes the number of foraminifera belonging to deep infaunal taxa, not directly related with depth, some of which are seen as indicators of stress conditions (S taxa). We have followed here the list of S taxa proposed by Van der Zwaan *et al.* (1990) and updated by Van Hinsbergen *et al.* (2005). Accordingly, the following taxa: *Bolivina* spp. (except *Bolivina pseudoplicata*), non-costate *Bulimina* (in our material *Bulimina aculeata* and *Bulimina elongata*), *Cancris* spp., *Fursenkoina* spp., *Globobulimina* spp., *Uvigerina* spp., including *Siphouvigerina hispida* (Fig. 3.17) and *Siphouvigerina proboscidea* and *Valvulinaria* spp., were computed as S taxa and thus excluded to calculate $\%P'$.

Planktonic foraminiferal species were classified according to their temperature preferences following Bicchi *et al.* (2003), based on previous studies by Bé & Hutson (1977) and Spezzaferri (1992). According to this scheme, four categories were distinguished: cool, cool-temperate, warm-temperate and warm water indicators. Following Bicchi *et*

al. (2003), in this study the species included in each category are: 1) cool: *Globigerina* spp. Here *Globigerina bulloides* (Fig. 4.6), *Globigerina* aff. *G. diplostoma* and *Globigerina falconensis* (Fig. 4.7), *Catapsydrax* spp., and *Turborotalita quinqueloba*; 2) cool-temperate: *Globorotalia scitula* (Fig. 4.15) and *Globoturborotalita woodi*; 3) warm-temperate: *Globigerinella obesa* (Fig. 4.8), *Globoquadrina dehiscens* (Fig. 4.11), *Globoquadrina venezuelana*, *Paragloborotalia mayeri* (Fig. 4.12), and aff. *Tenuitella angustumibilicata* (Fig. 4.18); 4) warm: *Globigerinoides* spp., including here *Trilobatus quadrilobatus* (Fig. 4.10), *Dentoglobigerina altispira* (Fig. 4.5), *Globorotalia praemenardii* (Figs 4.13-4.14) and *Orbulina* spp.

A palaeothermic estimation curve was then generated from the sum of warm + warm-temperate species percentages (positive numbers) and cool + cool-temperate species (negative numbers).

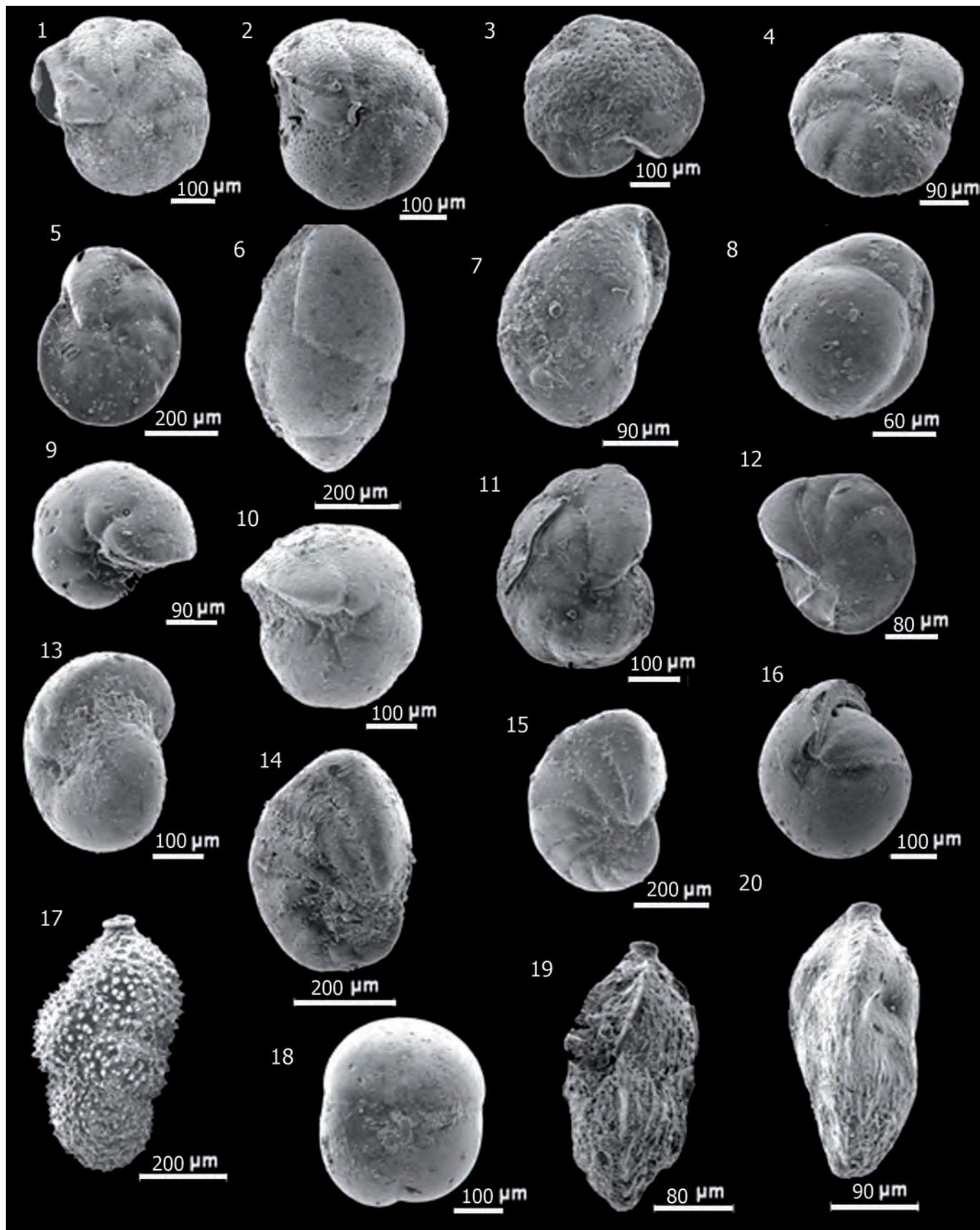
In addition, benthonic species were classified according to their oxygen preferences. Following Kaiho (1994) and Gebhardt (1999) three categories were considered: 1) oxic species, indicating oxygen contents >1.5 ml/l: *Heterolepa dutemplei*, *Heterolepa praecincta* (Fig. 3.12), *Cibicides* spp., *Cibicidoides* spp. and *Globocassidulina subglobosa* (Fig. 3.8); 2) suboxic indicators (groups B and C of Kaiho, 1994), most frequent with oxygen concentrations of 0.3-1.5 ml/l: species of *Cassidulina*, *Fissurina*, *Gyroidina* including *Hansenisca soldanii* (Fig. 3.10), *Lagena*, *Lenticulina* including *Neolenticulina peregrina* (Fig. 2.13), *Melonis*, *Nonion*, *Oridorsalis*, *Pullenia*, *Uvigerina*, *Trifarina*, *Valvulinaria*, *Sphaeroidina bulloides* (Fig. 3.18) and some *Bulimina* (e.g. *B. aculeata* and *B. striata*), *Dentalina* and certain *Stilostomellidae*, e.g. *Neugeborina longiscata*; 3) dysoxic indicators, characteristic of low oxygen concentrations (0.1-0.3 ml/l): *Bolivina* spp., *Laevidentalina* spp., *Fursenkoina* and *Globobulimina* spp.

The Benthic Foraminiferal Oxygen Index (BFOI), developed by Kaiho (1994) and expressed as $BFOI = 100*(O/O+D)$, where O and D are the number of specimens of respectively oxic and dysoxic indicators, was also calculated.

3. RESULTS

A list of all the foraminiferal species identified in the studied section of Canals can be found in Table 1

Figure 2. SEM images of foraminifera found in the Miocene beds of Canals. 1) *Martinottiella communis*. 2) *Martinottiella gaudryinoidea*. 3) *Siphonotularia affinis*. 4) *Amphicoryna hirsuta*. 5) *Dentalina vertebralis*. 6) *Glandulina laevigata*. 7) *Laevidentalina communis*. 8) *Laevidentalina mucronata*. 9) *Lagena striata*. 10) *Lenticulina calcar*. 11) *Lenticulina gibba*. 12) *Lotostomoides asperula*. 13) *Neolenticulina peregrina*. 14) *Saracenaria italicica* Defrance, 1824. 15) *Siphonodosaria lepidula*. 16) *Strictocostella advena*.



(Supplementary Information). In general, the degree of preservation is relatively good, but many specimens are small-sized or show sedimentary infillings that somewhat hinders the taxonomic identification. Diversity, palaeodepth and palaeothermic curve estimations together with BFOI and suboxic taxa relative abundance are all represented in Figure 5.

3.1. Planktonic foraminifera

The number of taxa in the planktonic assemblages, identified at least up to the genus level, ranges from 2 (at 0 m) to 16 (at 2.30 m). The relative abundance of some of the most frequent/relevant taxa throughout the section can be found in Figure 6. The samples are largely dominated by *Globigerina bulloides* (Fig. 4.6), whose frequency varies between 20% and 85% of the assemblage. This is the only planktonic species continuously occurring throughout the whole section and, in most samples, it groups more than 50% of the collected planktonic tests. Subdominant species are *Globorotalia praemenardii* (Figs 4.13-4.14), which exceeds 40% at 2.10 m, or *Globorotalia scitula* (Fig. 4.15), which shows a peak (~25% of the assemblage) at 0.20 m. Also common, but irregularly distributed, are *Globoquadrina dehiscens* (Fig. 4.11), *Globigerinita glutinata* (Fig. 4.9) and *Trilobatus quadrilobatus* (Fig. 4.10), together with the less represented *Globigerinita uvula* and aff. *Tenuitella angustumbilicata* (Fig. 4.18). The remaining species are very scarce, including some potential biostratigraphical markers, such as *Dentoglobigerina altispira* (Fig. 4.5) or *Paragloborotalia mayeri* (Fig. 4.12).

3.2 Benthonic foraminifera

Up to 142 benthic taxa were recognized in total (mostly Rotaliida and Lagenida) and the species richness in each sample varied between 25 (at 2.50 m) and 53 (at 2.10 m). Diversity is high (Fig. 5a), with Fisher alpha values varying between 15 and 25 and Shannon N1 between 15 and 31 throughout most of the studied profile. No discernable pattern is observed. In the uppermost sample (2.50 m), both diversity indices fall to their minimum scores (alpha index: 9 and Shannon N1: 11.85).

Figure 7 shows the relative abundance of the main taxa along the section. Unlike the planktonic assemblages, no particular benthic foraminiferal species is overwhelmingly

dominant. *Uvigerina barbatula* (Fig. 4.2) is the most abundant species; it represents more than 30% of the assemblage at the base of the section (0 m) and fluctuates between 5 and 20% in the other samples. *Globocassidulina oblonga* (Fig. 3.7) also occurs throughout the whole profile but it only exceeds 5% of the assemblage between 0.20 and 0.60 m. Other species above 10% of the assemblage in at least one sample include *Haynesina depressula*, with two prominent peaks at 0.60 and 1.70 m, or *Bulimina inflata*, most abundant in the middle part of the section (from 0.80 to 1.70 m). In the same category, *Melonis pompilioides* (Fig. 3.13), *Pullenia bulloides* (Fig. 3.16) and *Sphaeroidina bulloides* (Fig. 3.18) are more frequent in the upper part of the series, which is also the case of *Globobulimina affinis* (Fig. 3.6), although this latter species is only common in the uppermost sample. Also quite common are the Stilostomellidae, mainly represented by *Strictocostella advena* (Fig. 2.16), together with *Caveastomella adolphina*, *Siphonodosaria consobrina*, and *Siphonodosaria lepidula* (Fig. 2.15), with a prominent peak near the base of the series (> 25% at 0.20 m) and gradually decreasing upwards (Fig. 7). Other relatively frequent (> 5%) but less abundant species are *Cibicides floridanus* (Fig. 3.1), *Cibicides haidingeri* (Fig. 3.2), *Cibicidoides lobatulus* (Fig. 3.3), *Cibicidoides pseudoungerianus*, *Gyroidina umbonata* (Fig. 3.9), *Hansenisca soldanii* (Fig. 3.10), *Heterolepa praecincta* (Fig. 3.12), or *Oridorsalis tenerus*.

3.3 Palaeoenvironmental parameters

3.3.1 P:B ratio

Planktonic foraminifera represent above 50% of the total (planktonic + benthic) foraminiferal assemblages in all samples, with only one exception (39.46% at 2.30 m), and show a maximum of 91.34% at 0.60 m. The estimated paleodepth resulting from the regression developed by De Rijk *et al.* (1999) based on western Mediterranean data is shown in Figure 5b (a similar equation developed by these authors for the eastern Mediterranean yielded nearly identical results). Although there is a wide variation range (135 to 1582 m), most estimations fall in the interval 200-1000 m, corresponding to the middle-upper bathyal realm. The use of the expression determined by Van der Zwaan *et al.* (1990) yields a similar pattern but with less extreme

Figure 3. SEM images of foraminifera found in the Miocene beds of Canals. 1) *Cibicides floridanus*. 2) *Cibicides haidingerii*. 3) *Cibicidoides lobatulus*. 4) *Cibicidoides robertsonianus*. 5) *Cibicidoides ungerianus*. 6) *Globobulimina affinis*. 7) *Globocassidulina oblonga*. 8) *Globocassidulina subglobosa*. 9) *Gyroidina umbonata*. 10) *Hansenisca soldanii*. 11) *Hanzawaia boueana*. 12) *Heterolepa praecincta*. 13) *Melonis pompilioides*. 14) *Nonion boueanum*. 15) *Nonion commune*. 16) *Pullenia bulloides*. 17) *Siphouvigerina hispida*. 18) *Sphaeroidina bulloides*. 19) *Trifarina angulosa*. 20) *Trifarina bradyi*.



values (185 to 951 m), with all samples but one (2.10 m) included in the interval 200-1000 m (Fig. 5b).

3.3.2. Thermic curve

The palaeothermic curve inferred from the composition of the planktonic foraminiferal assemblages is shown in Figure 5c. Values oscillate between -94.8 and -2.7 and are always negative, thus pointing to rather cool waters. This estimation mostly derives from the notable dominance of the cool water indicator species *G. bulloides*. The curve shows some minor scale fluctuations within an apparently warming trend towards the top of the studied interval, reflected in a general increase of warm and warm-temperate water species like *G. praemenardii* or *G. dehiscens*.

3.3.3 BFOI

As other measured parameters, the BFOI curve (Fig. 5c) does not show any distinct pattern along the studied section but it systematically takes positive values, always $\geq +50$, with the sole exception of the uppermost sample (+32), thus, suggesting relatively well-oxygenated waters throughout most of the series. This is reflected in oxic indicators (mostly *Cibicides* spp. and *Cibicidoides* spp.) exceeding dysoxic indicators (mainly represented here by *Bolivina* spp. and *Globobulimina* spp.) in most studied samples. Nevertheless, it should be pointed out that, in all samples, the most abundant category is still that represented by the suboxic species (also displayed in Fig. 5c).

4. DISCUSSION

4.1 Biostratigraphy

Several authors have redefined and improved the middle Miocene biostratigraphy for the Mediterranean area, based on planktonic foraminifera and calcareous nannoplankton from extensive well-preserved sections in Malta, Sicily, the Tremiti Islands (Adriatic Sea) and the Italian Peninsula (e.g. Foresi *et al.*, 1998, 2001, 2002a, 2002b; Hilgen *et al.*, 2000, 2003; Di Stefano *et al.*, 2002, 2008; Lirer *et al.*, 2002, 2007; Sprovieri *et al.*, 2002a, 2002b; Lirer &

Iaccarino, 2011). As already pointed out by previous works (e.g. Martinotti, 1981; Huddleston, 1984; Mazza, 1985; Miller *et al.*, 1985, 1991; Coccioni *et al.*, 1992), their results reflect that some plankton events in tropical open ocean waters are diachronous with respect to middle-high latitudes or to the Mediterranean Sea.

In the short section studied in Canals *Globorotalia praemenardii* (Figs 4.13-4.14) is the most abundant and conspicuous biostratigraphical marker. In the open ocean, tropical to subtropical waters, Wade *et al.* (2011) established its first occurrence (FO) in their M6 Zone (= N9 Zone of Blow, 1969, upper Langhian). According to Kennett & Srinivasan (1983), its last occurrence (LO) is in the upper Serravallian (Zone N12 of Blow). In the Mediterranean Sea, the FO of this species has been recorded in the upper Langhian (Foresi *et al.*, 1998), and constitutes one of the best foraminiferal events to approximate the Langhian/Serravallian boundary (Iaccarino *et al.*, 2004). Lirer *et al.* (2007) and Di Stefano *et al.* (2008) locate this event at the top of Subzone MMi5b of the biostratigraphic scheme of Sprovieri *et al.* (2002b) and Iaccarino *et al.* (2004). Although the species becomes scarce in the upper part of its range, Foresi *et al.* (1998) placed its LO close to the Serravallian/Tortonian boundary (Fig. 8).

Another important, but unfortunately much scarcer, biostratigraphical marker in Canals is *Paragloborotalia mayeri* (Fig. 4.12). Eleven tests attributed to this species have been recovered from the topmost two samples of the studied section, where they represent 1-2% of the planktonic assemblage. This species is very similar to *Paragloborotalia siakensis*, which has been considered a junior synonym by some authors (Bolli & Saunders, 1982, 1985; Hilgen *et al.*, 2000; Turco *et al.*, 2001), whereas others differentiate between the two species (e.g. Blow, 1969; Kennett & Srinivasan, 1983; Iaccarino, 1985; Foresi *et al.*, 1998, 2001, 2002a, 2002b; Turco *et al.*, 2002; Hilgen *et al.*, 2003; Zachariasse & Sudijono, 2012). Although the recovered specimens in Canals are generally small and poorly preserved, some show features considered as distinctive of *P. mayeri* (e.g. curved sutures in the spiral side vs. straight radial spiral sutures in *P. siakensis*). In the tropical and subtropical open oceans, the stratigraphic range of *P. mayeri* extends from Zone O7 (Chattian, upper Oligocene) to the top of Zone M11 (Tortonian, upper Miocene) in the biostratigraphic scheme of Wade *et al.* (2011). However, in the Mediterranean Sea (and also in the North Atlantic, see Lirer & Iaccarino, 2005) this species

Figure 4. SEM images of foraminifera found in the Miocene beds of Canals. 1) *Uvigerina auberiana*. 2) *Uvigerina barbatula*. 3) *Valvulinaria complanata*. 4) *Catapsydrax unicavus*. 5) *Dentoglobigerina altispira*. 6) *Globigerina bulloides*. 7) *Globigerina falconensis*. 8) *Globigerinella obesa*. 9) *Globigerinita glutinata*. 10) *Trilobatus quadrilobatus*. 11) *Globoquadrina dehiscens*. 12) *Paragloborotalia mayeri*. 13) *Globorotalia praemenardii* spiral view. 14) *Globorotalia praemenardii* umbilical view. 15) *Globorotalia scitula*. 16) *Orbulina suturalis*. 17) *Orbulina universa*. 18) aff. *Tenuitella angustumbilicata*.

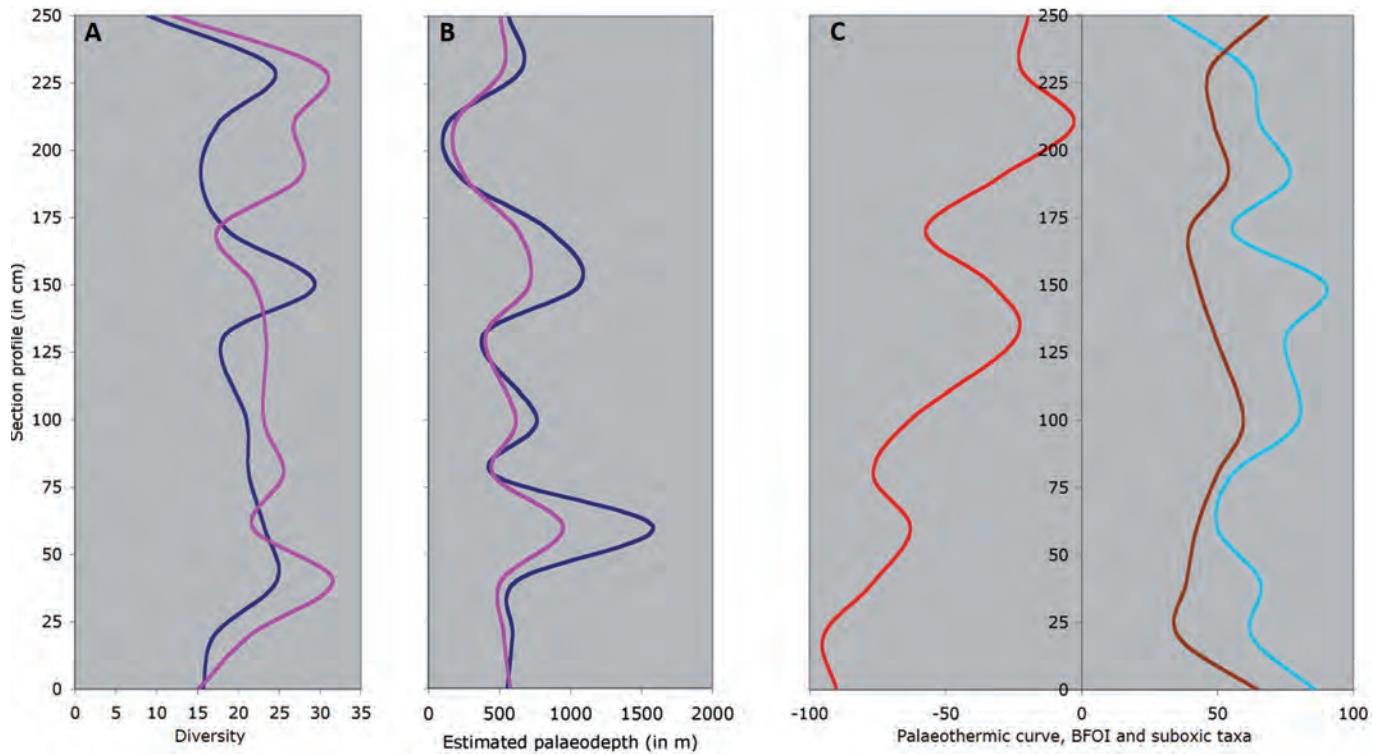


Figure 5. a) Benthic foraminiferal assemblages diversity along the studied section in Canals expressed by the Fischer alpha (blue) and Shannon-Wiener H' (pink) indices. The Shannon index H' is represented in the form $N1 = e^{H'}$ (see text). b) Palaeodepth estimation (in m) along the studied section in Canals based on the foraminiferal planktonic/benthic ratio and the expressions developed by De Rijk *et al.* (1999) for the recent western Mediterranean (blue) and by Van der Zwaan *et al.* (1990) (pink). c) Palaeothermic curve based on the composition of planktonic foraminiferal assemblages (red), oxygen index BFOI (light blue), and percentage of suboxic species (brown, groups B and C of Kaiho, 1994) along the studied section in Canals.

displays a much narrower range (Foresi *et al.*, 1998, 2001, 2002b). Its FO is difficult to detect but its first common occurrence (FCO) and LO define the specific subzone MM7b within the Serravallian (Sprovieri *et al.*, 2002b).

The rest of planktonic foraminifera recovered in Canals show longer stratigraphic ranges or are scant. Nevertheless, all are coherent with a Serravallian age (see Fig. 8). In a detailed description of the Miocene series in the Tremiti Islands (Adriatic Sea), Foresi *et al.* (2001) place the first occurrence of the long-range extant *G. bulloides* (Fig. 4.6) in the later defined Subzone MM7a (Sprovieri *et al.*, 2002b), although the FO of this species in the open ocean is in zone O5 (Chattian, upper Oligocene). On the other hand, *G. dehiscens* (Fig. 4.11), which is relatively abundant at the uppermost part of the studied section in Canals (> 20% at 2.50 m), disappears in Tremiti somewhere near the Serravallian-Tortonian boundary (Foresi *et al.*, 2001; but see Iaccarino, 1985, who extends its range up to the Tortonian in the Mediterranean), thus slightly preceding the last regular occurrence (LRO) of *Dentoglobigerina* spp., located in the lowermost Tortonian (Foresi *et al.*, 2002b; Iaccarino *et al.*, 2004). *Dentoglobigerina altispira* (Fig. 4.5) is very rare in Canals (only 4 specimens in the upper

half of the studied section), but its occurrence together with *G. dehiscens* and other “globoquadrinids” suggests that the studied samples might precede, or at least be contemporaneous with the Serravallian *Globoquadrina* decline in the Mediterranean reported by various authors (e.g. Martinotti, 1981; Zachariasse & Spaak, 1983).

The occurrence of aff. *Tenuitella angustumibilicata* (Fig. 4.18) in Canals deserves a specific comment. This taxon is common in most of the studied section (although it never exceeds 10% of the assemblage). According to Kennett & Srinivasan (1983), *T. angustumibilicata* (as *Globigerina angustumibilicata*) is one of the longest-ranging Cenozoic foraminiferal species (Eocene–Pliocene) and Foresi *et al.* (2001) reported it throughout the Miocene in the Tremiti islands (as “*Globigerina*” gr. *angustumibilicata*–*quinqueloba*). However, according to Pearson *et al.* (2018), *T. angustumibilicata* became extinct in the early Miocene and younger occurrences reported in the Neogene probably refer to homeomorphic forms. Since its taxonomic status is uncertain we have left this taxon here as aff. *Tenuitella angustumibilicata*.

Other foraminiferal species used as biostratigraphical markers in the central Mediterranean are absent or have

not been recognized in Canals. This can be attributed either to different taxonomic criteria, different specific environmental conditions or the palaeogeographical location of the studied section, near the Nord-Betic Strait, in close contact with the Atlantic. Therefore, the age of the studied section of Canals is Serravallian, and probably upper Serravallian, above subzone MMi7a, but the extreme scarcity of the important stratigraphic marker *P. mayeri* prevents further precision.

The proposed age for the *tap* marls of the locality of Canals is thus in agreement with previous studies of Colom (1936), Usera (1972, 1973, 1974a, 1974b, 1975) and Calvo Sorando *et al.* (1974), on the marine Miocene outcrops in the south of the Valencia Province. It is also consistent with the results of Gebhardt (1999) in the north of the Alicante Province. This author establishes a Serravallian transgressive phase with conglomerates and calcarenites, on which the *tap* marls would have been deposited during the Serravallian-Tortonian with no apparent discontinuity. The species reported in IGME (1976), which were used to ascribe these beds to the Tortonian, have not been found in our studied section.

4.2 Palaeobathymetry

As already pointed out, the results of the P:B ratios suggest a middle-upper bathyal environment (200-1000 m, with average estimations of 525-650 m) for the studied section in Canals (Fig. 5b). The important presence throughout most of the studied section of planktonic species like *G. scitula*, that require a minimum depth of ~500 m (Bé & Tolderlund, 1971; Martins & Dragão Gomes, 2004), and the composition of the benthic foraminiferal assemblages, are more or less in agreement with this estimation, although in many cases foraminiferal distribution is mainly controlled by factors others than depth. Some of the main benthic species (exceeding 10% of the assemblage in at least one sample), such as *S. bulloides* (Fig. 3.18), *P. bulloides* (Fig. 3.16) or *M. pompilioides* (Fig. 3.13) are typically found in outer neritic and/or bathyal environments in modern oceans (Culver & Buzas, 1981, 1982, 1983). This is also the case of *Globocassidulina* spp. or many current species of *Uvigerina* (Murray, 2006). In particular, *Uvigerina barbatula* (Fig. 4.2) is one of the dominant species in the Serravallian section studied in San Nicola

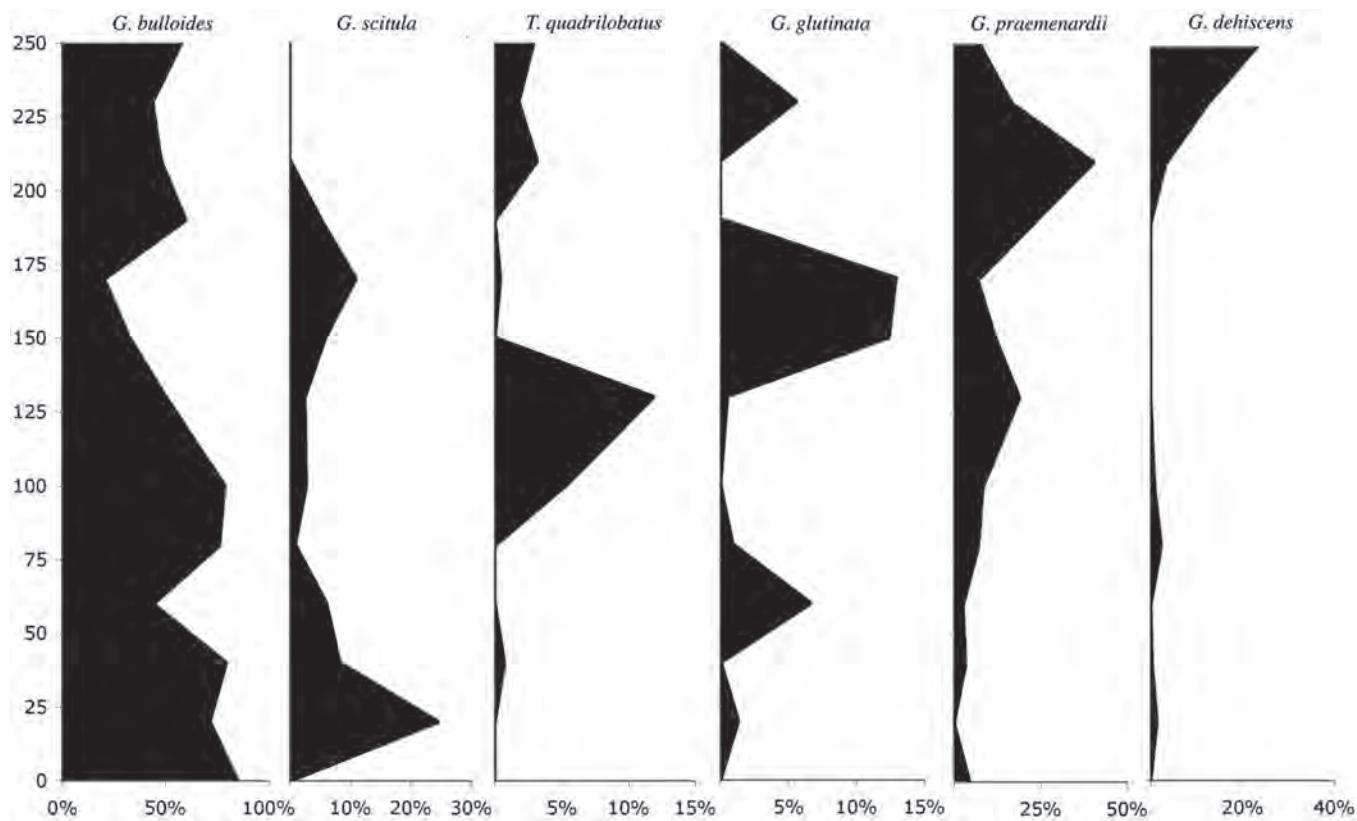


Figure 6. Relative abundance of the main planktonic foraminiferal species (>10% in at least one sample) along the studied section in Canals.

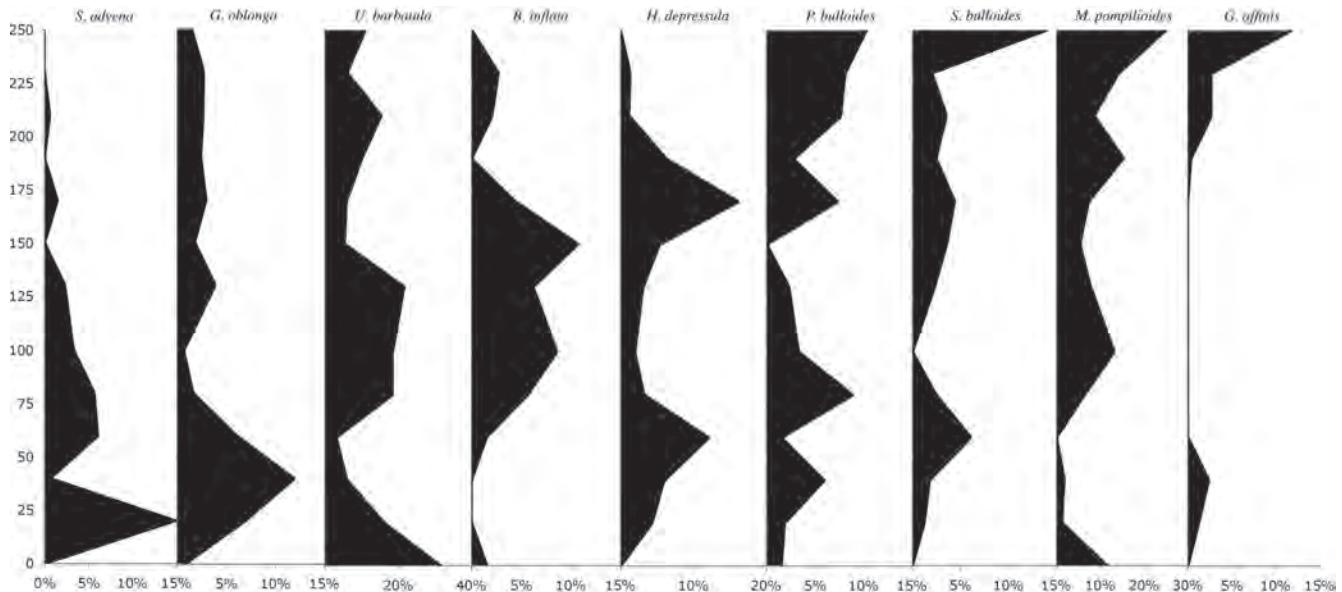


Figure 7. Relative abundance of the main benthic foraminiferal species (>10% in at least one sample) along the studied section in Canals.

(Tremiti islands, Adriatic), with an estimated palaeodepth of around 1000 m (Russo *et al.*, 2002). A similar bathymetric distribution is shown in present day oceans by other species, less abundant but still common in Canals, like *H. soldanii* (Fig. 3.10) or *G. umbonata* (Fig. 3.9). Lower bathyal indicators such as *Cibicidoides wuellerstorfi*, *Oridorsalis umbonatus*, *S. hispida* (Fig. 3.17) or *O. tenerus* represent as a whole only ~3% of the assemblage on average, which is still below the 5% limit considered by Gebhardt (1999) as an indication of truly lower bathyal (≥ 1000 m) environments.

On the other hand, the occurrence of the inner neritic species *H. depressula* suggests that part of the foraminiferal tests may have been transported by currents from shallower areas, even if this species only exceeds 10% of the total benthic assemblage in two of the less representative samples (0.60 and 1.70 m), with <100 benthic tests recovered. Therefore, the estimations based on P:B ratios should be regarded with caution. Nevertheless, the whole available data are mostly coherent with an upper-middle bathyal environment for the studied section in Canals. The location of the North Betic Strait, within the outer Prebetic, would allow the formation of relatively deep basins (≥ 600 m). The later tectonic evolution would close the communication with the Atlantic Ocean, eventually resulting in the establishment of a series of restricted basins and the deposit of lacustrine materials on these Miocene marls (Calvo *et al.*, 1978).

4.3 Palaeoenvironmental conditions

The section studied in Canals is too limited (2.50 m) to reflect long-term climatic evolution. The apparently

warming trend shown by the planktonic assemblages (Fig. 5c) might thus represent a local short-time climate fluctuation within the global cooling tendency during the Serravallian, originated in the increasing extension of the East Antarctic Ice Sheet (e.g. Miller *et al.*, 1991; Flower & Kennett, 1993, 1994; Turco *et al.*, 2001; Zachos *et al.*, 2001; Bicchi *et al.*, 2003; Lirer *et al.*, 2004). Alternatively, this pattern may simply reflect a short-term decrease of the prevailing upwelling conditions. The occurrence in these beds, and not in others included in the so-called blue marls (IGME, 1976), of numerous diatoms, radiolarians and sponge spicules are indicative of coastal upwelling phenomena, as those corresponding to the “Intermediate Episode” described in the Guadalquivir Basin (López García & Bustillo, 1994). During this “Episode” the high productivity of the oceanic waters in the North Betic Strait became generalized and coincided with a relative tectonic stability. The interruption or restriction of upwelling cool deep waters would also result in an effective temporal warming of the water mass and in assemblages less dominated by relatively cool water species like *G. bulloides*, that has also been associated to phytoplankton blooms and upwelling phenomena (Hemleben *et al.*, 1989; Thunell & Sautter, 1992; Pujol & Vergnaud Grazzini, 1995; Martins & Dragão Gomes, 2004).

A first appraisal of the BFOI index results (Fig. 5c) indicates a high oxic environment along most of the studied section, with an estimated range of 3– ≥ 6 ml/l of dissolved oxygen according to Kaiho (1999) and Murray (2006). However, the methodological approach, with the use of only categories B and C of Kaiho (1994) for suboxic indicators and the >125 μm instead of the >250 μm

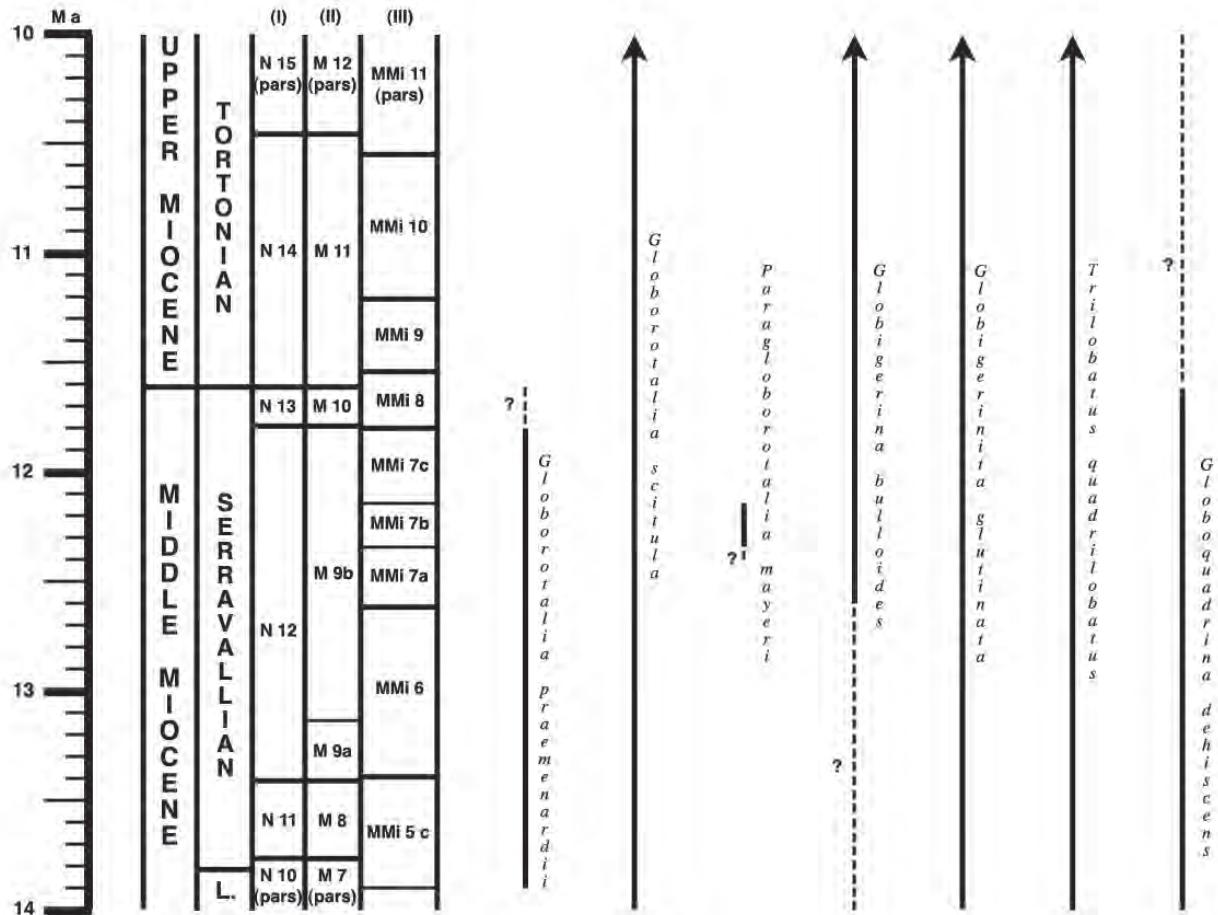


Figure 8. Mediterranean biostratigraphic ranges of some planktonic foraminiferal species found in Canals compared with the biostratigraphic schemes of (I) Blow (1969) and (II) Wade *et al.* (2011) for the tropical open ocean, and (III) Sprovieri *et al.* (2002b) and Iaccarino *et al.* (2004) for the Mediterranean. Equivalences between (I) and (II) are based on Wade *et al.* (2011). Boundary absolute ages follow the astronomical time scales of Lourens *et al.* (2004) for (I) and (II), and Laskar *et al.* (1993) for (III). Ranges of the foraminiferal species are based on several sources (see text). L = Langhian.

size-fraction employed by Gebhardt (1999), thus including many smaller mainly infaunal species (e.g. *Bulimina*, *Bolivina* or *Uvigerina* spp.), requires caution when interpreting the index BFOI in terms of specific ranges of dissolved oxygen. *Uvigerina barbatula*, the most abundant benthic species in Canals, is a suboxic indicator that tolerates a moderate oxygen deficiency. Nevertheless, Russo *et al.* (2002) found it associated with oxic species like *C. ungerianus* (Fig. 3.5), *C. wuellerstorfi* or *H. dutemplei* as the dominant species of an assemblage indicative of relatively well oxygenated waters in Serravallian deep bathyal (~1000 m) sediments of the Tremiti islands (Adriatic Sea).

On the other hand, the high relative abundance of suboxic species (~50% on average, see Fig. 5c), with numerous large Stilostomellidae, well-developed specimens of *Dentalina*, *Laevidentalina*, *Lenticulina* and abundant *Uvigerina* and *Gyroidina* spp., and the estimated depth range (upper-middle bathyal) for the Canals section

suggest the influence of an Oxygen Minimal Zone (OMZ), but without a severe deficiency of dissolved oxygen, like in the Langhian-Serravallian section studied by Bellanca *et al.* (2002) in Ras-II-Pellegrin (Malta). This would rather indicate a medium to low oxic environment (~1.2–3.2 ml/l for Kaiho, 1999 or 1.5–3 ml/l for Murray, 2006).

The high diversity of the assemblages (Fisher and Shannon indices) together with the aforementioned abundance of diatoms, radiolaria and sponge spicules also point to the prevalence of coastal upwelling conditions with high surface productivity and carbon flux that would involve a certain degree of oxygen consumption. The uppermost part of the section, with the sharp decrease of the BFOI and diversity indices together with the rise of the dysoxic species *G. affinis* (Fig. 3.6), marks a certain environmental deterioration with less ventilated waters. In addition to the observed short-term warming inferred from the planktonic assemblages, this may indicate a temporal slowing or interruption of up-welling currents

and consequently a more sluggish circulation and more stagnated waters towards the top of the studied section.

5. CONCLUSIONS

As inferred from the abundant occurrence of *G. praemenardii* the Miocene marls from the locality of Canals, in the south of the Valencia Province, can be ascribed to the Serravallian, within the open ocean zones N 10 to N 12 of Blow (1969), or M 7 to M 9 of Wade *et al.* (2011), which correspond to biozones MMi 5c to MMi 7 in the Mediterranean scheme of Sprovieri *et al.* (2002b) and Iaccarino *et al.* (2004). A more specific assignation to the upper Serravallian would require confirming the occurrence of the extremely scarce species *P. mayeri* or the analysis of other biostratigraphical markers (e.g. calcareous nannoplankton).

The studied materials were deposited in an upper-middle bathyal environment as inferred from both the B:P ratios and the benthic foraminifera depth-markers. The plankton composition (foraminifera and abundant diatoms and radiolaria) is coherent with the climate cooling that developed during the middle Miocene as a consequence of the extension of the Antarctic Ice Cap and with the (possibly local) prevalence of upwelling phenomena, such as those identified in coetaneous materials from the Guadalquivir Basin. Within this context, the planktonic foraminifera suggest a short-term climate warming or, alternatively, a temporal episode of interruption / slowing of upwelling currents resulting in warmer waters towards the top of the studied section. In agreement with this, the highly diverse benthic foraminifera are consistent with an environment of high productivity and carbon flux and only a moderate deficiency in oxygen (low-medium oxic environment), reflecting the possible influence of a paleo-OMZ that is expected to be present at upper-middle bathyal depths. The constriction of upwelling currents towards the top of the section would eventually result in a more sluggish water circulation, a less oxygenated bottom and less diverse foraminiferal assemblages.

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