raphy, biostratigraphy and cyclostratigraphy in the Mediterranean. *Earth Planet. Scien. Lett.*, 136: 475-494, Amsterdam.

Laskar J., Joutel F. & Boudin F. (1993) - Orbital, precessional, and insolation quantities for the Earth from -20 Myr to +10 Myr. Astron. *Astrophys.*, 270: 522-533, Paris.

Lirer F., Caruso A., Foresi L.M., Sprovieri M., Bonomo S., Di Stegano A., Di Stefano E., Iaccarino S.M., Salvatorini G., Sprovieri R. & Mazzola S. (2002) - Astrochronological calibration of the upper Serravallian/lower Tortonian sedimentary sequence at Tremiti Islands (Adriatic Sea, Southern Italy). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 241-256, Milano.

Lourens L.J. (1996) - Astronomical forcing of Mediterranean climate during the last 5.3 million years. Ph.D Thesis., V. of 247 pp., Utrecht.

Martini E. (1971) - Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A: (ed.), Proc. II Planktonic Conference, Roma (1970), 2: 739-785, Roma.

Mazzei R. (1985) - The Miocene Sequence of the Maltese Islands: Biostratigraphic and chronostratigraphic references based on nannofossils. *Atti Soc. Tosc. Sci. Nat., Mem.*, Ser. A, 92: 165-197, Pisa

Okada H. & Bukry D. (1980). Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry 1973, 1975). *Mar. Micropal.*, 5: 321-325, Amsterdam.

Olafsson G. (1989) - Quantitative calcareous nannofossil biostratigraphy of upper Oligocene to middle Miocene sediment from ODP Hole 667A and Middle Miocene sediment from DSDP Site 574. In: Ruddiman W., Sarnthein M. et al. (eds.). Proc. ODP, Sci. Results, 130: 245-256, College Station (TX).

Olafsson G. (1991) - Quantitative calcareous nannofossil biostratigraphy and biochronology of early through late Miocene sediments from DSDP Hole 608. Medd. *Stockjolms Univ. Inst. Geol. Geochem.*, 203-IV, 28 pp., Stockholm.

Pareto L. (1865) - Note sur les subdivisions que l'on pourrait étabilir dans les terrains tertiaires de l'Apennin septentrional. *Bull. Soc. Géol. Fr.*, sér. 2, 22: 210-217, Paris.

Pedley H.M., House M.R., Waugh B. (1976) - The geology of Malta and Gozo. *Proc. Geol. Ass.*, 87 (3): 325-341, London.

Pedley H.M., House M.R., Waugh B. (1978) - The geology of the Pelagian block: the Maltese Islands. In: Nairn A.E.M., Kanes W.H., Stehli F.G. (eds.) - The Ocean basins and margins: the Western Mediterranean. Plenum Press, New York and London: 417-433, New York.

Perch-Nielsen K. (1985) - Cenozoic calcareous nannofossils. In: Bolli H.M., Saunders J. B. & Perch-Nielsen K. (eds.) - Plankton Stratigraphy. Cambridge Univ. Press. 1: 427-554, Cambridge.

Raffi I. & Flores J.A. (1995) - Pleistocene through Miocene calcareous nannofossils from Eastern Equatorial Pacific Ocean (LEG 138). In: Pias N.G., Mayer L.A., et al. (eds.). Proc. ODP, Sci. Results, 138: 233-286, College Station (TX).

Raffi I., Rio D., d'Atri A., Fornaciari E. & Rocchetti S. (1995) - Quantitative distribution patterns and biomagnetostratigraphy of middle and late Miocene calcareous nannofossils from equatorial Indian and Pacifics oceans (Legs 115, 130 and 138). In: Pias N.G., Mayer L.A., et al. (eds.). Proc. ODP, Sci. Results, 138: 479-502, College Station (TX).

Reuther C.D. & Eisbacher G.H. (1985) - Pantelleria Rift: Crustal extention in a convergent intraplate setting. *Geol. Rundsch.*, 74: 585-597, Hannover.

Rio D., Raffi I. & Villa G. (1990). Pliocene-Pleistocene calcareous nannofossil distribution patterns in the western Mediterranean. In: Kastens et al. (eds.). Proc. ODP, Sci. Results, 107, 513-533, College Station (TX).

Robertson A.H.F. & Grasso M. (1995) - Overview of the Late Tertiary-Recent tectonic and paleo-environmental development of the Mediterranean region. *Terra Nova*, 7: 114-127, Oxford.

Salvatorini G. & Cita M.B. (1979) - Miocene foraminiferal stratigraphy, DSDP Site 397 (Cape Bojador, North Atlantic). In: Ryan W.B.F. et al. (eds.). Init. Reports. DSDP, 47(1): 317-373, Washington (U.S. Government Printing Office).

Shackleton N.J., Berger A., Peltier W.R. (1990) - An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Trans. R. Soc. Edinb., 81: 251-261, Edimburg.

Shackleton N.J., Baldauf J.G., Flores J.-A., Iwai M., Moore T.C. Jr., Raffi I., & Vincent E. (1995) - Biostratigraphy summary for Leg 138. In: Pisias N.G., Mayer L.A., Janecek T.R, et al. (eds.). Proc. ODP, Sci. Results, 138: 517-536, College Station (TX).

Shackleton N.J. & Crowhurst S. (1997) - Sediment fluxes based on orbital tuned time scale 5 MA to 14 MA, site 926. In: Shackleton N.J., Curry W.B., et al. (eds.). Proc. ODP, Sci. Results, 154: 69-82, College Station (TX).

Spezzaferri S. (1994) - Planktonic foraminiferal biostratigraphy and taxonomy of the Oligocene and Lower Miocene in the oceanic record. An overview. *Palaeont. Italica*, 81: 1-187, Pisa.

Sprovieri M., Caruso A., Foresi L.M., Bellanca A., Neri R., Mazzola S. & Sprovieri R. (2002) - Astronomical calibration of the upper Langhian/lower Serravallian record of Ras-Il Pellegrin section (Malta Island, Central Mediterranean). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 183-193, Milano.

Sprovieri R. (1992) - Mediterranean Pliocene biochronology: an high resolution record based on quantitative planktonic foraminifera distribution: *Riv. It. Paleont. Strat.*, 98: 61-100, Milano.

Sprovieri R. (1993) - Pliocene-Early Pleistocene astronomically forced planktonic foraminifera abundance fluctuations and chronology of Mediterranean calcareous plankton bio-events. *Riv. It. Paleont. Strat.*, 99:. 371-414, Milano.

Sprovieri R., Di Stefano E., Becquey S., Bonomo S. & Caravà N. (1996a) - Calcareous plankton biostratigraphy and cyclostratigraphy at the Serravallian-Tortonian boundary. *Paleopelagos*, 6: 437-453, Roma.

Sprovieri R., Di Stefano E., Caruso A. & Bonomo S. (1996b) - High resolution stratigraphy in the Messinian Tripoli formation in Sicily. *Paleopelagos*, 6: 415-435, Roma.

Rivista Italiana di Paleontologia e Stratigrafia | volume 108 | numero 2 | pagine 223-239 | Luglio 2002

EVOLUTION OF THE MEDITERRANEAN BASIN DURING THE LATE LANGHIAN - EARLY SERRAVALLIAN: AN INTEGRATED PALEOCEANOGRAPHIC APPROACH

ADRIANA BELLANCA [1], FRANCA SGARRELLA [2], RODOLFO NERI [3], BIANCA RUSSO [4], MARIO SPROVIERI [5], GIOACCHINO BONADUCE [6] & DANIELA ROCCA [7]

Received July 15, 2001; accepted January 22, 2002

Keywords: Middle Miocene, Island of Malta, Mediterranean Sea, benthic foraminifera, stable isotopes, paleoceanography, paleoecology.

Riassunto. Lo studio microfaunistico e geochimico della sezione composita di Ras il-Pellegrin (Isola di Malta, Mediterraneo centrale), riferita all'intervallo Langhiano superiore-Serravalliano inferiore, ha permesso di ricostruire le condizioni paleoambientali in questo settore del Mediterraneo durante il Miocene medio.

I foraminiferi bentonici e gli ostracodi indicano una paleobatimetria di circa 500 m e condizioni al fondo di lieve sottossigenazione. Alcuni episodi riconosciuti, caratterizzati da associazioni oligotipiche (alti valori percentuali del gruppo *Bulimina elongata*), indicano una ulteriore riduzione dell'ossigenazione. Pertanto si ipotizza che i sedimenti studiati si siano depositati in prossimità o in corrispondenza di una zona di minimo di ossigeno.

Due episodi di aumentata produttività superficiale (valori più elevati di Ba e $\delta^{13}C$), sono stati individuati, rispettivamente alla base e nella parte alta della successione, e posti in relazione con fenomeni di upwelling e maggiore runoff. Il primo, caratterizzato dall'abbondanza di *B. costata*, è correlabile con l'evento a scala globale di Monterey. Il secondo episodio, rappresentato da valori negativi del $\delta^{13}C$ dei foraminiferi bentonici e da abbondanza di *Uvigerina peregrina*, indica maggiore preservazione di materia organica al fondo e rallentamento della circolazione nel sistema termoalino del Mediterraneo. I bio-eventi ricostruiti sono stati calibrati su scala astrocronologica utilizzando i dati ciclostratigrafici ottenuti dalla stessa sezione.

Il confronto dei dati ottenuti con quelli su sedimenti coevi di altre aree del Mediterraneo (DSDP Site 372 e 375; nuovi dati sulle successioni delle Isole Tremiti) suggerisce che la paleocircolazione nel bacino durante l'intervallo studiato fosse caratterizzata da tre diverse masse d'acqua: 1) acqua atlantica di superficie che entrava nel Mediterraneo; 2) acqua intermedia che si originava in superficie nel Mediterraneo orientale e fluiva nell'Atlantico; 3) acque di fondo fredde atlantiche (psicrosferiche) che entravano nelle aree profonde del Mediterraneo.

Abstract. An integrated (multidimensional) faunal and geochemical dataset has been generated by the study of a Middle Miocene sedimentary section (Ras il-Pellegrin) outcropping in the Malta Island (central Mediterranean) and referred to the Late Langhian-Early Serravallian interval.

Benthic foraminifera and ostracods suggest a paleobathymetry of about 500 m and slightly under-oxygenated bottom conditions for the deposition of the sediments. Some bio-events, characterized by oligotypical assemblages (*Bulimina elongata* group high percentage values) indicating stressed bottom conditions and very low oxygen content, seem related to suboxic episodes.

Periods of enhanced surface productivity, indicated by increasing Ba concentrations and by $\delta^{13}C$ values measured in planktonic foraminifera, are recorded at the base and in the upper part of the succession and suggest the combination of upwelling events and enhanced continental runoff. In particular, the lower interval has been correlated with the C-isotope Monterey event. The upper interval, characterized by negative excursions in the benthic carbon isotope curve, combined with the appearance of benthic species indicative of increasing preservation of organic carbon at the bottom of the basin, suggests a general reduced Mediterranean thermoaline circulation system during the upper Langhian-early Serravallian. These events are calibrated to the astrochronologic scale proposed for the same section by cyclostratigraphic analysis.

Benthic assemblages and isotope evidence, combined with information from other coeval Mediterranean sediments (DSDP Site 375, Site 372; new data from Tremiti Islands), allow us to interpret the large-scale thermoaline circulation in the Mediterranean basin during Middle Miocene. Three discrete water masses have been identified: 1) surface Atlantic water inflowing into the Mediterranean; 2) intermediate outflowing Mediterranean water originated in the surficial eastern end; 3) atlantic (psychrospheric) bottom water identified in different areas of the basin.

Introduction

In the last decades, integrated faunal and geochemical datasets were collected from deep sea records

[1] Dipartimento di Chimica e Fisica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy, e-mail: bellanca@unipa.it
[2] Dipartimento Scienze della Terra Università Federico II, Largo San Marcellino,10, 80138 Napoli, Italy, e-mail: garella@unina.it
[3] Dipartimento di Chimica e Fisica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy, e-mail: neri@unipa.it
[4] Dipartimento Scienze della Terra Università Federico II, Largo San Marcellino,10, 80138 Napoli, Italy, e-mail: brusso@unina.it
[5] Dipartimento di Chimica e Fisica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy, e-mail: marios@unipa.it
[6] Dipartimento di Chimica e Fisica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy, e-mail: gbona@unina.it
[7] Dipartimento di Chimica e Fisica della Terra (CFTA), Via Archirafi 36, 90123 Palermo, Italy.

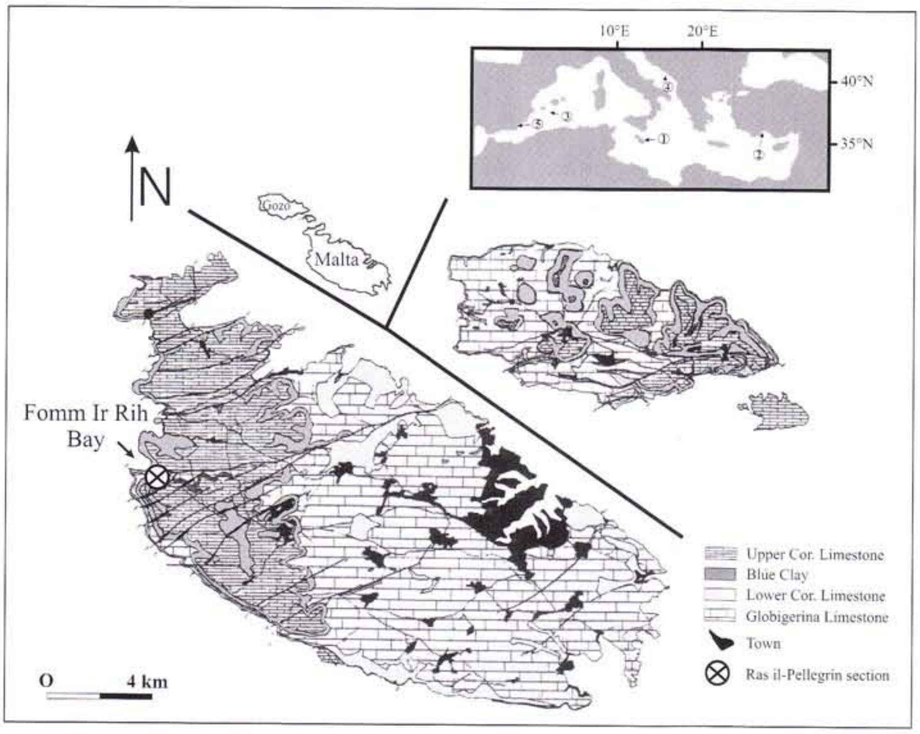

Fig. 1 - Location map of the sections and DSDP/ODP sites mentioned in the text. 1-Ras il-Pellegrin; 2-DSDP Leg 42 Site 372; 3-DSDP Leg 42 Site 375; 4-Tremiti islands; 5- Alicante.

of the oceans in order to unravel the evolution of climate and oceanography during the Cenozoic. Recent studies (e.g. Pinardi & Masetti 1999) demonstrated the importance of the Mediterranean basin as a "natural laboratory" for the study of climatic and oceanographic mechanisms recorded on a wide scale. Datasets from the Mediterranean sediments are substantially confined to the Late Neogene and also their scattered geographical distribution limits paleoceanographic reconstructions on a basin scale. There are presently many unsolved questions on the Mediterranean basin evolution during the Langhian-Serravallian stratigraphic interval, which was characterized by a global climatic and oceanographic reorganization due to the stepwise build-up of the Antarctic ice cap (Savin et al. 1981; Shackleton & Kennett 1975; Woodruff & Savin 1991).

In this paper, we propose an integrated study of a Middle Miocene central Mediterranean composite succession (Ras il-Pellegrin section) outcropping in the western margin of the Malta Island and referred to the late Langhian - early Serravallian on the basis of biostratigraphic information (e.g. Felix 1973; Debono et al. 1993). The studied sediments are referred by Pedley et al. (1976) to a shelf domain, the "Ragusa platform", extended from Malta to Sicily. In particular, we present a dataset of benthic foraminiferal assemblages, stable isotopes obtained by planktonic and benthic species. Our data are integrated with detailed bio- and cyclostratigraphic results from the same section (Sprovieri et al. 2002; Foresi et al. 2002) and correlated with ostracods paleoecology (Bonaduce & Barra 2002), with the aim to provide new insights for paleoecological reconstructions. Moreover, we compare our results with those reported in the literature for other coeval Mediterranean

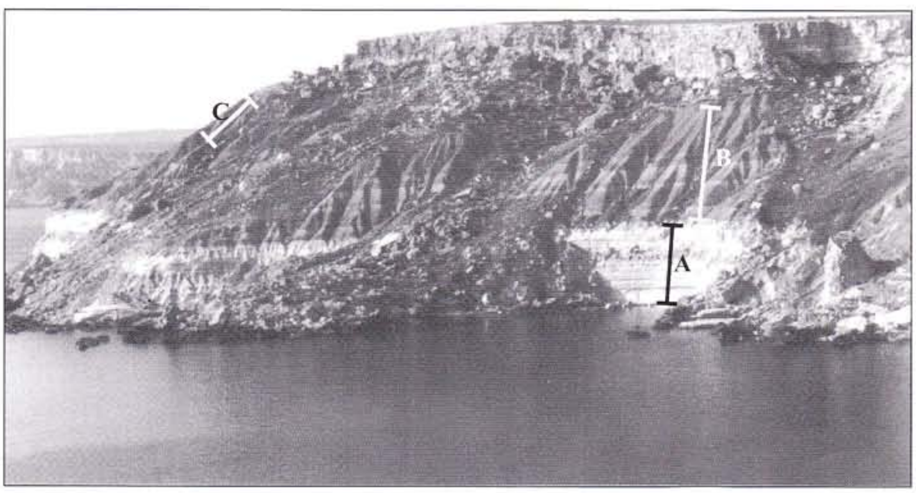

Fig. 2 - A general view of the Ras il-Pellegrin section with segments A, B and C indicating the sampled sedimentary intervals.

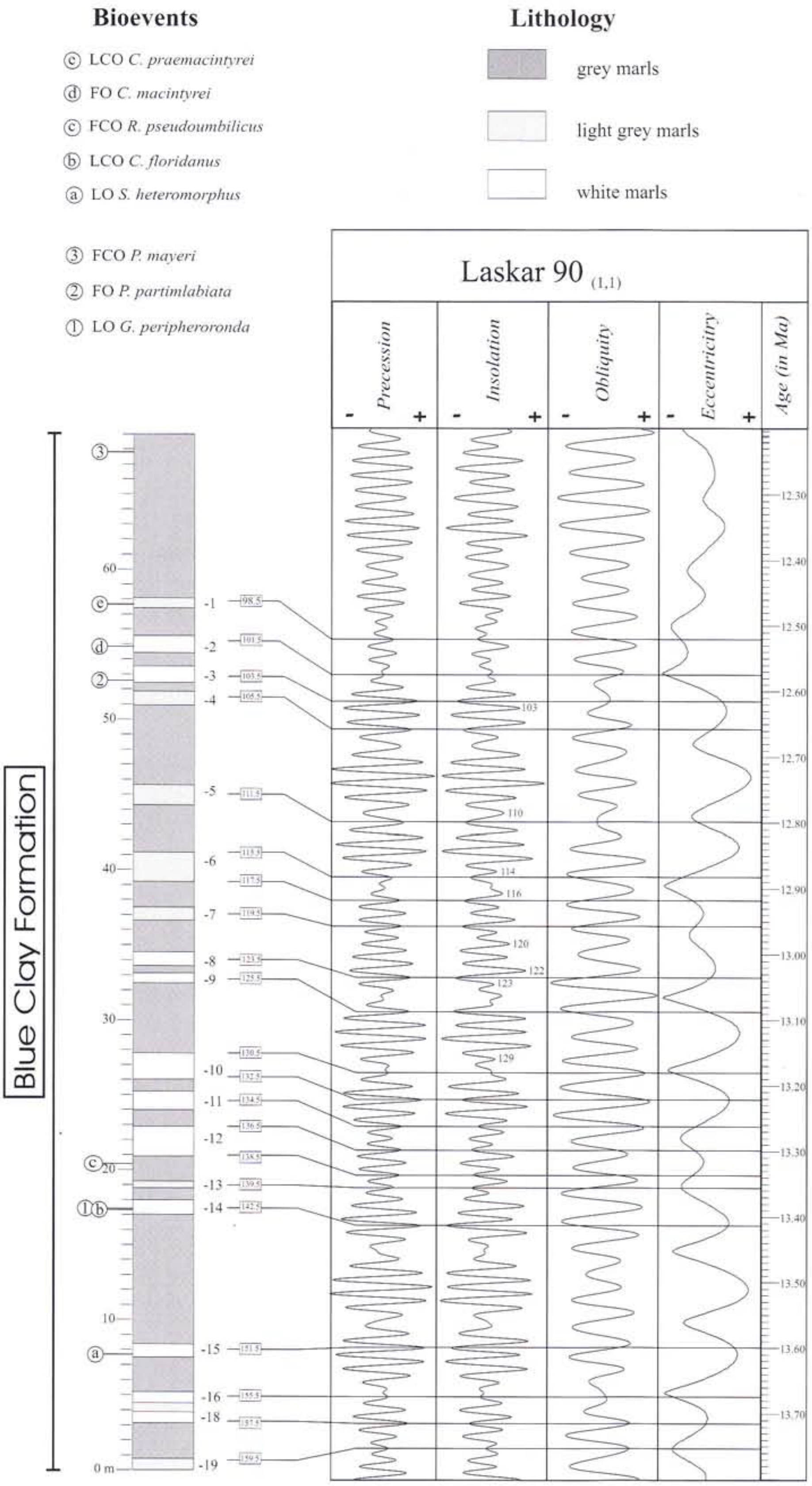

Fig. 3 - Astronomical tuning of the Blue Clays Formation in the Ras il-Pellegrin composite section and position of the main calcareous plankton events (by Sprovieri et al., 2002). White layers coincide with more carbonatic intervals. Correlation between the lithologic cycles and the astronomical solution of Laskar et al. (1993) with present-day values for tidal dissipation and dynamical ellipticity of the Earth are reported.

areas in order to tentatively reconstruct the distribution pattern of water masses during the considered interval.

Materials and chronology

The investigated area of Ras il-Pellegrin is located in the north-western margin of the Malta Island, about 20 km west of the Valletta town, in the northern side of the Fomm ir-Rih Bay (Fig. 1). In this area the following formations crop out in stratigraphic order: Middle and Upper Globigerina Limestone, Blue Clay and Upper Coralline Limestone (Hyde 1955; Giannelli & Salvatorini 1975; Felix 1973; Pedley et al. 1976, 1978; Debono et al. 1993; Foresi et al. 2002).

We have studied the Globigerina Limestone Formation - Upper member and the Blue Clay Formation. We sampled a composite section (Fig. 2) constituted by the Globigerina Limestone Formation - Upper member (segment C), about 22 m thick, referred to late Langhian (Foresi et al. 2002) and by the Blue Clay Formation, about 68.8 m thick, consisting of blue/grey pelagic marls interbedded with thick pale bands. In particular, to obtain the longest and best exposed sedimentary record from the Blue Clay Formation, we have reconstructed a composite succession formed by two segments, (segment A and B) correlated on the basis of lithologic and biostratigraphic information (for details see Sprovieri et al. 2002).

Our integrated faunal and geochemical study was mainly focused on the upper Langhian-lower Serravallian part of the Blue Clay Formation.

A detailed calcareous plankton biostratigraphy (planktonic foraminifera and calcareous nannofossils) of the Ras il-Pellegrin section has been obtained by Foresi et al. (2002). The most important calcareous plankton bioevents are reported along with the lithologic column in Fig. 3. Moreover, a detailed cyclostratigraphic analysis has been carried out on the sediments of the same section by Sprovieri et al. (2002) and an astronomical calibration for this sequence is now available. In Fig. 3 (simplified after Sprovieri et al. 2002) astronomical ages for the recorded biostratigraphic events are reported together with the obtained correlation of the sediments with the different components of the insolation curve of Laskar et al. (1993).

Methods

Benthic foraminiferal analyses have been performed on 221 samples from the Blue Clay Formation (mean sampling interval 30 cm). Moreover, 15 samples have been investigated also from the underlying Globigerina Limestone Formation - Upper member. All the benthic specimens were picked out, identified and counted from the fraction > 125 μm. The residue was split with a microsplitter to yield a sub-sample containing more than 200 benthic specimens. Taxon abundance is expressed as percentage of the total fauna. The benthic number (BN) was calculated as the total number of specimens in the fraction >125 μm per gram of dry sediment and reported as BN >125 μm.

The quantitative data were elaborated by Q-mode Factor Analysis using the CABFAC program (Imbrie & Kipp 1971; Klovan & Imbrie 1971).

Oxygen and carbon isotopes were measured on specimens of the planktonic foraminifer *Globigerinoides quadrilobatus* and benthic foraminifer *Cibicidoides ungerianus* for a total of 140 and 40 samples, respectively. We assume the oxygen isotope values of *G. quadrilobatus* and *C. ungerianus* to be indicative of surface and deep water isotope composition, respectively, with a constant offset from oxygen isotopic equilibrium.

About 25 specimens per sample, picked from the >150 μm size fraction, cleaned ultrasonically for about 2 min, were roasted for 40 min at 450°C in high vacuum glass tubes to remove organic matter. Then, the foraminifers were transferred into glass reaction tubes and dissolved in 100% phosphoric acid at 25°C under high vacuum for 12 hours. The obtained CO_2 was cryogenically separated from other gases and measured with a Finnigan Delta S mass spectrometer. The isotopic results are expressed in δ‰ units and reported against the PDB-1 standard. The reproducibility for the isotopic determinations was 0.1‰ for $\delta^{18}O$ and 0.07‰ for $\delta^{13}C$.

Ba concentrations were measured on a total of 17 bulk samples homogenously distributed throughout the studied section. Ba analysis has been performed by X-ray fluorescence spectrometry (XRF) on bulk-rock pressed pellets using the method of Franzini et al. (1975) for matrix corrections. The accuracy of determinations was checked by using certified reference materials.

Numerical methodologies of spectral analysis are based on the standard procedure of Weedon (1991).

Results

Benthic foraminiferal assemblage

Globigerina Limestone Formation - Upper member.

The benthic foraminiferal assemblage is characterized by a number of common and abundant species, such as *Cibicidoides ungerianus* (sensu Papp & Schmid 1985, pl. 51, figs. 7-11), *Uvigerina rutila, U. barbatula, Siphonina reticulata, Cibicidoides subhaidingerii* (sensu Van Morkhoven et al. 1986, pl. 28, figs. 1a-c), together with *Gyroidina soldanii, Spiroplectinella carinata* and *Melonis pompilioides* as subordinate species. BN >125 μm shows very high values ranging from 620 to 2130 specimens per gram of dry sediment, with average value of 1452.

However, our main interest was focused on the overlying Blue Clay Formation.

Blue Clay Formation.

The distribution of dominant, common or significant species, which characterize the benthic foraminiferal assemblage, is reported in Fig. 4. *C. ungerianus, C. subhaidingerii, U. rutila-barbatula* group, *Bulimina elongata* group, mostly represented by *B. lappa*, together with rare specimens of the typical morphotype and *B. elongata subulata* are common and abundant species together with *Siphonina reticulata*, as subordinate species. We separately counted *C. subhadingerii* from *Cibicidoides dutemplei* even if they have a close similarity, as suggested by Van Morkhoven et al. (1986). The percentages of *U. rutila* and *U. barbatula*, which are the most abundant species, are lumped together with *U. kusterii* and *U. striatissima* within the *U. rutila-barbatula* group. Additional and significant species are: *Bulimina costata, Uvigerina peregrina, Gyroidina* spp. (mostly *G. soldanii*), *U. pygmaea, Pullenia bulloides, Bolivina reticulata, Bolivina dilatata, Uvigerina proboscidea, Spiroplectinella carinata, Anomalinoides helicinus, Astrononion umbilicatulum, Globobulimina* spp. and very rare specimens of *Cibicidoides wuellerstorfi*, which are scattered throughout the section. We also recorded very rare specimens of *Ammonia*, typical genus of the infra-littoral zone all along the section. These forms are interpreted as displaced.

C. ungerianus, C. subhaidingerii and *U. rutila-bar-*

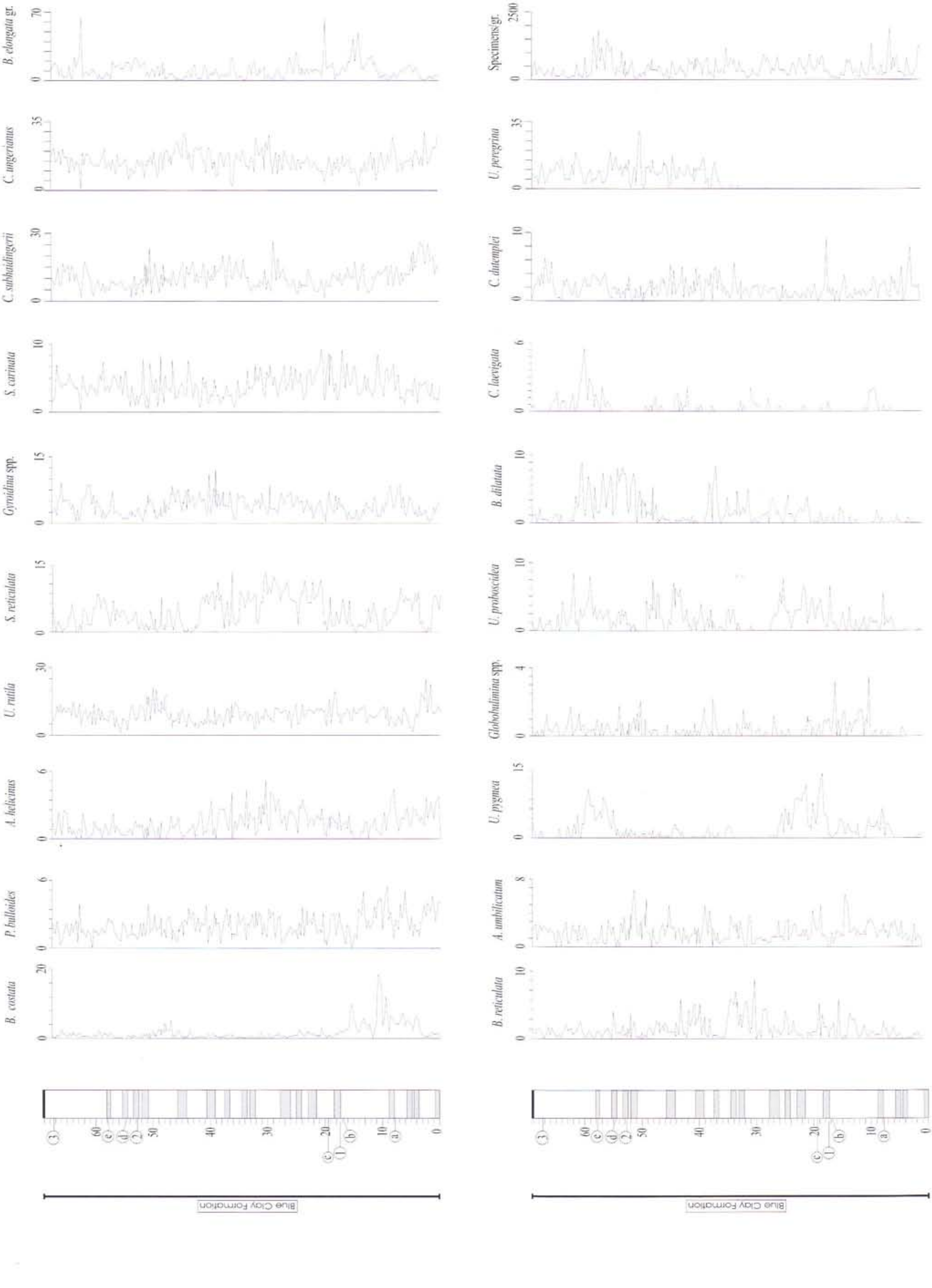

Fig. 4 - Distribution (percentage values) of the dominant, common and significant benthic foraminiferal species throughout the Blue Clays Formation in the Ras il-Pellegrin composite section. Biostratigraphic events are reported as in Fig. 3.

batula group are dominant throughout all the succession, fluctuating in the range of 10-20%, 5-20% and 5-15%, respectively. The *B. elongata* group is also dominant, but its percentage strongly fluctuates in the range 1-25% with abundance peaks higher than 40-60% at 14.36 m, 14.98 m, 20.18 m and 63.54 m. *S. carinata* is always present, but it is never particularly abundant (2-8%). In more detail, several species show the following specific distributions: 1) *B. costata* and *P. bulloides*, as subordinate species, are abundant from the base of the succession up to about 16 m; 2) *U. peregrina* is common and relatively abundant from its appearance level at 35 m up to the top of the succession, with average percent values fluctuating in the range of 5 -15%; 3) *S. reticulata* and *A. helicinus* are relatively abundant from the base up to about 42 m and decrease in the upper part; 4) *U. pygmaea* shows two maxima, one between 17 and 25 m and the other between 54 and 60 m, with a strong reduction between 26 and 52 m; in this interval *B. reticulata* and *A. umbilicatulum* increase (Fig. 4); 5) *B. dilatata* is abundant in the 20-37 m and 47-61 m intervals, but it is rare in other intervals; 6) *U. proboscidea* is generally rare and increases in abundance in the 7-25 m, 33-48 m and 52-64 m intervals.

BN >125 μm is high, but values display strong fluctuations from 35 to 1951 specimens per gram of dry sediment, with an average value of 425 (Fig. 4).

Multivariate statistical analysis

The relative abundance of 30 species and 7 group of species (comprehensive taxonomic units) in 221 samples was elaborated by Q-mode Factor Analysis. The composed taxonomic units are *B. elongata* group, *Globobulimina* spp., *Gyroidina* spp., *Lenticulina* spp., *Martinottiella* spp., Nodosarids and *U. rutila-U. barbatula*. All the species with percentage values less than 2% have been discarded. Four factors have been rotated. They explain a total variance of 91%, with high to very high communalities. Rotated Varimax factor Scores are reported in Table 1. Varimax Factor Loadings are plotted versus depth in Fig 5.

Factor 1, which explains a variance of 27%, is dominated by *C. ungerianus*, with *S. reticulata* representing the second low scored component.

Factor 2, which explains a variance of 25%, is dominated only by the *B. elongata* group.

Factor 3, which explains a variance of 21%, is dominated by *C. subhaidingerii*, with *U. rutila/U. barbatula* and *B. costata* as low scored components.

Factor 4, which explains a variance of 17%, is dominated only by *Uvigerina peregrina*.

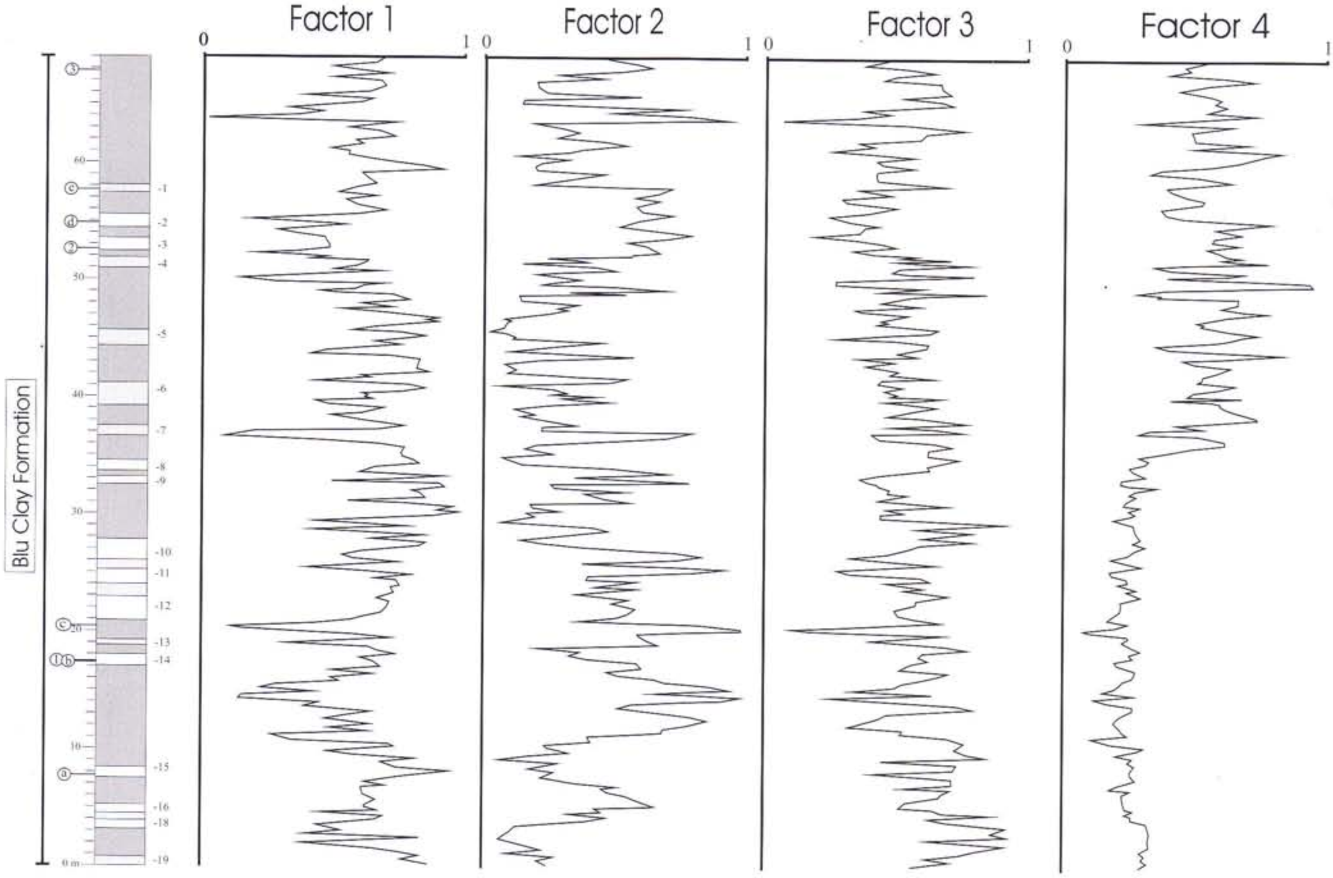

Fig. 5 - Factor scores obtained from the benthic foraminiferal assemblage Q-mode factor analysis of the Blue Clays Formation in the Ras il-Pellegrin composite section.

The first three factors display fluctuating values throughout all the section, but factor 4 has significant loading only in the upper part of the section, starting from about 35 m.

Stable isotopes

Depth profiles of both oxygen and carbon isotope compositions of the planktonic foraminifer *G. quadrilobatus* from the Ras il-Pellegrin section are shown in Fig. 6.

The planktonic $\delta^{18}O$ curve exhibits a series of high frequency ~1.5‰ variations superimposed on a long-term trend of upwards increasing values (mean values from about -1.7‰ at the base of the succession to about -1.2‰ at the top). A sequence of long-term modulations of the $\delta^{18}O$ curve has been identified with a maximum amplitude of 2.8‰.

The $\delta^{13}C$ curve exhibits high frequency oscillations mostly in a range of ±0.5‰. In particular, the isotope values gradually increase in a range of about 0.7‰ from the base of the section to about 12 m. Then, a negative excursion leads the carbon curve to mean values of about 1.0‰ up to about 30 m. Then, despite some negative spikes, the curve shows a trend towards more positive values upwards in the section.

Benthic $\delta^{18}O$ values (Fig. 6) throughout the succession moderately fluctuate around a mean value of about 0.3‰. Three long-term modulations, with amplitudes of about ±0.5‰ can be observed in the intervals 5-27 m, 27-54 m and 54-68 m.

The benthic carbon isotope curve exhibits a lightening upwards trend from the bottom of the section to about 20 m, shifting the $\delta^{13}C$ values from about 1.3 to 0‰. Then, a quasi-constant $\delta^{13}C$ value is observed throughout the remnant part of the succession with only low frequency oscillations modulating the isotope curve in the range of ±0.5‰. A final negative excursion, from about 50 m, shifts the carbon values to averages of about -0.4‰.

A comparison between benthic and planktonic $\delta^{18}O$ curves shows very similar trends with phased response to the medium length scale forcing. Conversely, comparison between benthic and planktonic $\delta^{13}C$ curve shows opposite trends.

Bulk sample Barium concentration

Barium concentration data (Fig. 7) from 20 whole-rock samples scattered throughout the section define a decreasing trend from the base up to 30 m of the section, shifting the Ba concentration from about 160 to about 75 ppm. Then, upwards in the section, Ba increases again up to about 260 ppm.

The Ba content in the sediments is considered a reliable indicator for surface water paleoproductivity studies because of its good correlation with C_{org} content in sediments and sediment traps (Dyamond et al. 1992; De Lange et al. 1994; Francois et al. 1995).

Barium precipitates as barite associated with organic matter in surface marine waters (Bishop 1988). Barite dissolution can occur throughout the water column or at the seafloor, as a result of sulphate reduction under very low dissolved oxygen conditions (Passier et al. 1999).

As reported below, benthic assemblage for the Ras il-Pellegrin section excludes euxinic depositional environments; the measured Ba content; can be considered a good tracer of surface productivity for the analyzed record. Thus, higher Ba concentrations in the lower and upper part of the section could reflect periods of relatively enhanced nutrient availability and surface productivity in the area.

Comparison between Ba concentration and Ba/Al ratio (Fig. 7) enabled us to reveal the presence of differences in the chemical characteristics of terrestrial matter,

Benthic species	Factors			
	I	II	III	IV
Angulogerina angulosa	0,044	0,039	0,039	-0,02
Anomalinoides helicinus	0,077	0,01	0,057	-0,033
Astrononion umbilicatulum	0,036	0,04	0,037	0,026
Bigenerina nodosaria	0,022	0,001	-0,006	-0,008
Bolivina arta	0,027	0,018	0,033	-0,002
Bolivina dilatata	0,005	0,066	-0,058	0,106
Bolivina reticulata	0,146	0,042	-0,041	0,002
Bolivina sp.	-0,002	0,004	0,005	0,011
Bolivina spathulata	0,029	0,01	-0,022	0,029
Bulimina costata	-0,045	0,085	**0,209**	-0,096
Bulimina elongata group	-0,109	**0,954**	-0,131	0,033
Bulimina exilis	-0,006	0,006	0,007	0,001
Cassidulina carinata	0,019	-0,001	-0,006	0,004
Cassidulina laevigata	0,024	-0,002	-0,013	0,011
Cibicidoides dutemplei	0,026	0,01	0,067	0,047
Cibicidoides subhaidingerii	-0,065	-0,022	**0,752**	0,194
Cibicidoides ungerianus	**0,867**	0,047	-0,01	0,2
Globobulimina spp.	-0,011	0,015	0,017	0,009
Globocassidulina subglobosa	0,04	-0,016	-0,001	0,019
Gyroidina spp.	0,13	0,006	0,048	0,064
Hanzawaia boueana	0,129	0,007	0,021	0,072
Lenticulina spp.	0,056	0,076	0,079	0,052
Martinottiella spp.	0,027	0,003	-0,001	0,003
Melonis pompilioides	0,062	0,019	-0,01	0,004
Nodosarids	0,01	0,079	0,144	0,038
Oridorsalis umbonatus	0,054	0,018	0,017	0,023
Pullenia bulloides	0,047	0,035	0,097	0,003
Pullenia quinqueloba	0,01	0,004	0,001	-0,005
Siphonina reticulata	**0,29**	0,055	0,045	-0,099
Sphaeroidina bulloides	0,024	0,003	-0,007	0,019
Spiroplectinella carinata	0,147	0,11	0,115	-0,031
Trifarina bradyi	0,054	0,023	0,025	-0,023
Uvigerina peregrina	-0,15	-0,059	-0,218	**0,916**
Uvigerina proboscidea	0,069	0,039	-0,038	0,03
Uvigerina pygmaea	0,09	0,102	-0,009	-0,068
Uvigerina rutila-U. barbatula group	-0,061	0,155	**0,502**	0,159

Tab. 1 - Principal component loadings obtained from the Factor analysis of the benthic foraminiferal assemblage of the Blue Clay Formation in the Ras il-Pellegrin composite section. The most significant variables are reported in bold.

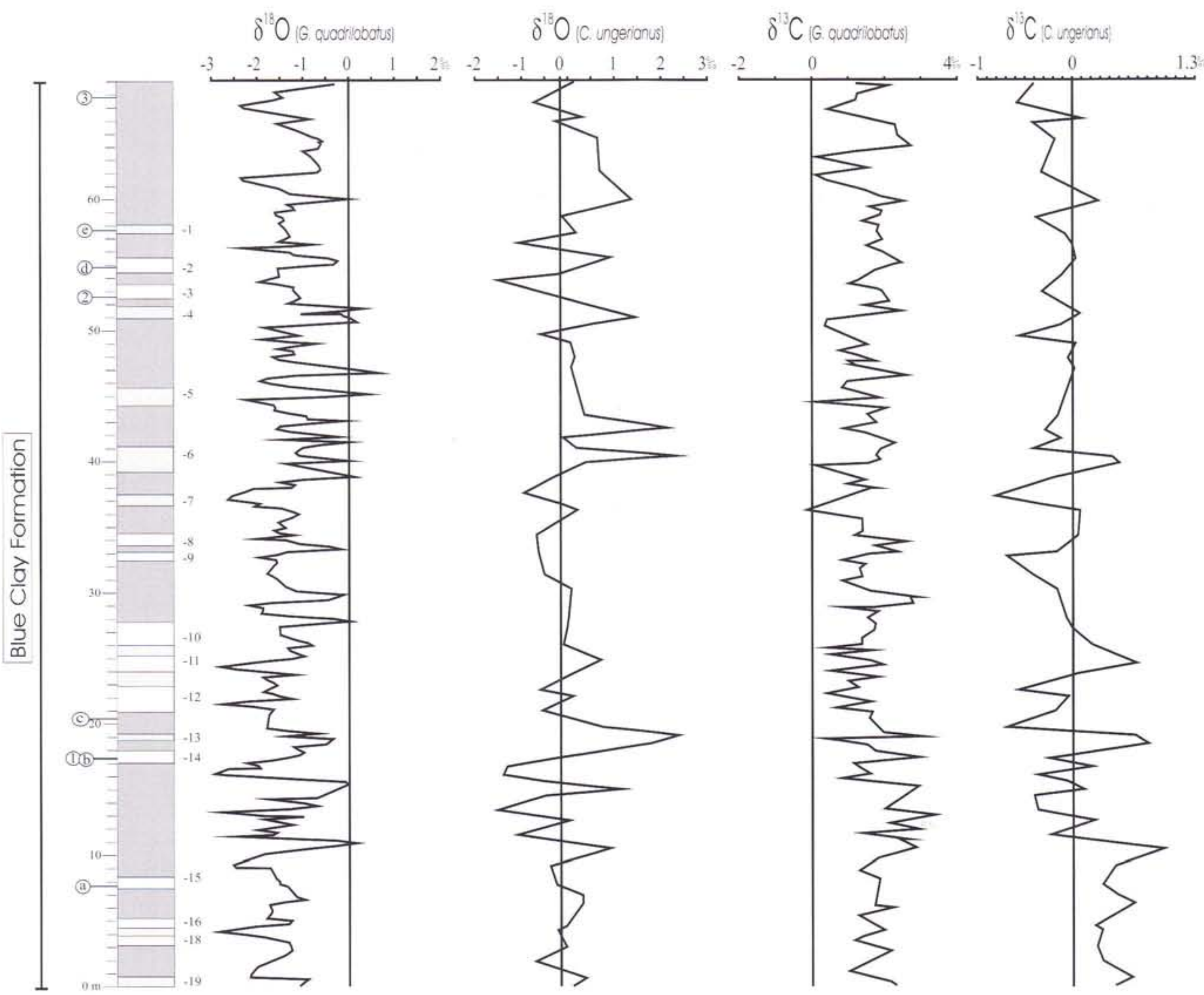

Fig. 6 - Oxygen and carbon isotope curves from the Blue Clays Formation in the Ras il-Pellegrin composite section for the selected planktonic (*G. quadrilobatus*) and benthic (*C. ungerianus*) foraminiferal species.

as suggested by Calvert & Pedersen (1993) and, consequently, to verify the usefulness of Ba as tracer of surface productivity changes in the studied record. The very similar behavior shown by the two curves suggests that chemical variations of the terrigenous matter cannot explain the recorded variability of Ba concentration in the sediments and that surface productivity changes could have represented an important mechanism driving the distribution of this element in the studied system.

Paleoecological interpretation

Paleobathymetry

The benthic foraminiferal assemblage in both Globigerina Limestone - Upper member and Blue Clay Formation is indicative of an upper bathyal environment. The contemporaneous presence and/or enhanced abundance of selected depth-limited species allow a reliable estimation of paleobathymetry of the analyzed sediments. In particular, *G. soldanii* is recorded at depth greater than 450 m in the Gulf of Mexico (Pflum & Frerichs 1976) and deeper than 500 m in the North Atlantic (Phleger et al. 1953); *C. dutemplei* is reported in depth range of outer neritic and upper bathyal (Van Morkhoven et al. 1986). *Cibicidoides wuellerstorfi*, a lower bathyal and abyssal species, is represented by very rare specimens all along the section. Van Morkhoven et al. (1986) indicate the rare occurrence of this species in correspondence with its upper depth limit at 500 m. Therefore, we estimate a paleobathymetry in the range of 500-600 m for the studied sediments. This result is consistent with a paleobathymetry of about 500 m inferred by Bonaduce & Barra (2002) on the basis of the presence of epibathyal ostracod species. In particular, the authors note the occurrence of *Oblitacythereis*, typical genus of thermospheric bottom water masses and the absence of *Agrenocytere*, genus indicative of psycrospheric bottom conditions.

Upper Globigerina Limestone *versus* Blue Clay Formation: bottom condition change

We have recognized remarkable differences in the co-dominant and subordinate assemblages of the Globigerina Limestone - Upper member and Blue Clay Formations. *Bolivina dilatata, Uvigerina peregrina, Uvigerina proboscidea, U. pygmaea* and other hispido-costate Uvigerinids (e.g. *U. kusterii, U. rugosa* and *U. hispida*) and *Globobulimina* spp. are recorded in the Blue Clay Formation, but they are absent or very rare in the Globigerina Limestone - Upper member. All these species are indicative of low oxygen bottom water conditions (Van der Zwaan 1982; Katz & Thunell 1984; Boersma 1984; Corliss 1985; Borsetti et al. 1986). In addition, the *Bulimina elongata* group is recorded with very low percentage in the Globigerina Limestone - Upper member (not more than 1%) compared with mean percentage values of about 10% and a great number of fluctuations and "anomalous" peaks around 50% or higher in the Blue Clay (Fig. 4). Van der Zwaan (1982) reported *B. elongata* as a species tolerant of oxygen deficiency. Therefore, we believe that the Blue Clay represent relatively stressed and poorly oxygenated bottom conditions, if compared with the Globigerina Limestone - Upper member. However, the very low percentage values of *Globobulimina* spp. (Fig. 4), a genus tolerant of very low oxygen content (Corliss 1985) and typical of dysoxic bottom conditions (sensu Kaiho 1994), demonstrate that the sedimentary environment of the Blue Clay Formation was not characterized by extreme under-oxygenated bottom conditions.

The average of BN > 125 μm is lower in the Blue Clay Formation (425 specimens per gram), as compared with the very high values of the Globigerina Limestone - Upper member (1452 specimens per gram). These data probably confirm a decrease in the oxygen bottom content from the Globigerina Limestone - Upper member vs. the Blue Clay Formations.

Furthermore, the specimen abundance and diversity recorded in the ostracod assemblages (Bonaduce & Barra 2002) of the Globigerina Limestone Formation - Upper member are very high (average 119 specimens and 19 species), as compared with that of the Blue Clay Formation (average 18 specimens and 5 species), also testifying the decrease in the oxygen conditions in this part of the sequence. Some samples at the top of the Blue Clay Formation are completely barren of ostracods, possibly indicative of very low oxygen content also in this part of the section.

Blue Clay paleoenviromental evolution

Q-mode Factor Analysis (Fig. 5) distinguished the following four benthic foraminiferal assemblages:

- Assemblage A (factor 1): *C. ungerianus* and *S. reticulata*. The first species is assumed as an oxic indicator by Van der Zwaan (1982). *S. reticulata*, an epifaunal to transitional species, is reported from areas with oxygen content of 1.5 ml/l (Rathburn & Corliss 1994; Rathburn & Miao 1995), considered a boundary value between suboxic and low oxic conditions sensu Kaiho (1994). Moreover, *S. reticulata* was considered tolerant of relatively low oxygen conditions, but able to live in an oxic environment (Sgarrella et al. 1999). Consequently, Factor 1 is considered indicative of relatively well oxygenated bottom water conditions.

- Assemblage B (Factor 2): *B. elongata* group. This group has been recorded mostly in muddy recent sediments of shelf areas (Murray 1991) and in front of river mouths (Iaccarino 1967; Pujos 1976; Bizon & Bizon 1984; Murray 1991; Sgarrella & Moncharmont Zei 1993; inter alios). Generally, zones influenced by runoff products are dominated by species with a tolerance to stressed conditions (Jorissen 1988). Only Mathieu (1988) recorded that this species increases in the offshore and upper slope in the upwelling area of the Atlantic continental margin of Morocco. As a result, the bathymetric previously reported distribution of this species becomes deeper in this upwelling area. Cita (1973) recorded a monotypical assemblage of *B. elongata* from the Messinian Gessoso-Solfifera Formation of Sicily just in the last fossiliferous level pre-dating the beginning of evaporites, with euxinic bottom conditions. Therefore, we believe factor 2 is indicative of a stressed bottom environment with very low oxygen concentrations.

- Assemblage C (factor 3): *C. subhaidingerii*, with *U. rutila-U. barbatula* group and *B. costata*. Generally *Cibicidoides* spp. group, epifaunal taxa with planoconvex or biconvex trochospiral tests, is considered indicative of oxic environments, in particular if they are larger than 350 mm (Corliss 1991; Kaiho 1994, among others). However, Van der Zwaan (1982) lumped *C. dutemplei* together with *C. subhaidingerii* (the last one reported as *C. ungerianus* variant intergrade) for the quantitative analyses and suggested that both species are tolerant of some oxygen deficiency. Also *U. rutila* is reported as a species tolerant of only moderate oxygen deficiency (Borsetti et al. 1986). *B. costata* is considered a species tolerant of relatively oxygen deficiency (Van der Zwaan 1982; Jonkers 1984). Therefore, we consider factor 3 as indicative of poorly oxygenated bottom conditions.

- Assemblage D (Factor 4): only *Uvigerina peregrina*. The present day distribution of *U. peregrina* is often related to high organic bottom content (Miller & Lohmann 1982; Lutze & Coulbourn 1984; Lutze 1986; Van Leeuwen 1986; Van der Zwaan et al. 1986; Miao & Thunell 1993) and/or low bottom water oxygen content (Pflum & Frerichs 1976; Lohmann 1978; Streeter & Shackleton 1979; Schnitker 1979, 1980, 1994). There-

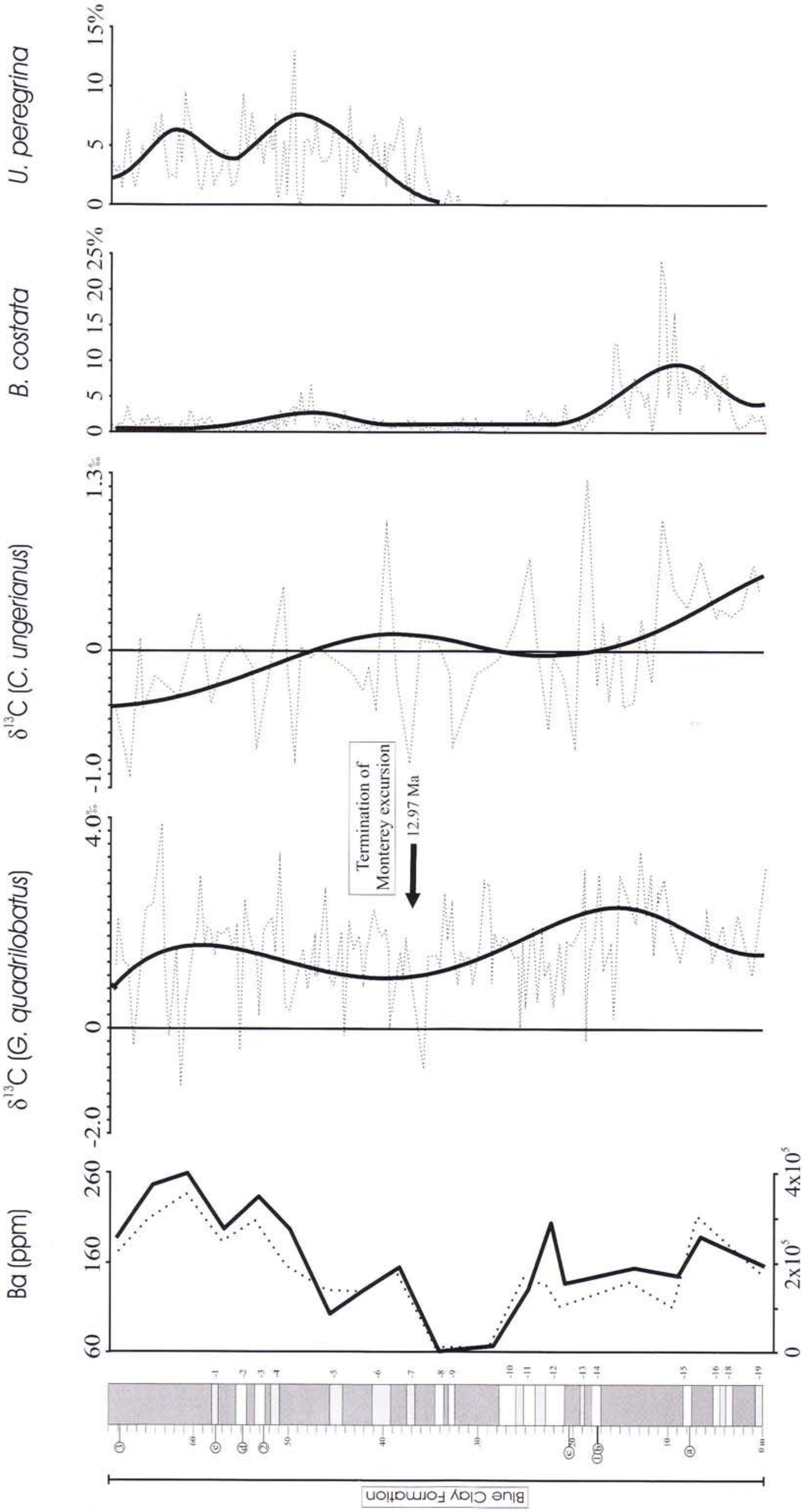

Fig. 7 - Comparison of the whole-rock Ba concentration, the planktonic and benthic $\delta^{13}C$ values and the *B. costata* and *U. peregrina* relative abundance throughout the Blue Clay Formation in the Ras il-Pellegrin composite section.

		C. subhadingerii		$\delta^{18}O_{planktonic}$		$CaCO_3$		*Globigerinoides*		Insolation	
		C	P.L.	C	P.L.	C	P.L.	C	P.L.	C	P.L.
C. ungerianus	21ky	.82	178°	.81	4°	.82	0°	.82	179°	.91	178°
	100ky	.87	180°	.78	358°	.87	0.5°	.91	181°	.89	185°
	400ky	.92	167°	.89	4°	.91	1°	.97	180°	.95	181°
C. subhadingerii	21ky			.94	182°	.91	181°	.89	2°	.95	1°
	100ky			.97	178°	.96	183°	.91	2°	.93	358°
	400ky			.89	181°	.89	176°	.97	357°	.89	3°
$\delta^{18}O_{planktonic}$	21ky					.79	2°	.94	178°	.76	181°
	100ky					.67	6°	.93	184°	.67	176°
	400ky					.92	358°	.89	181°	.74	178°
$CaCO_3$	21ky							.79	181°	.76	170°
	100ky							.76	178°	.65	176°
	400ky							.68	183°	.89	184°
Globigerinoides group	21ky									.64	0°
	100ky									.81	2°
	400ky									.94	358°

Tab. 2 - Coherency (C) and phase lag (P.L.) results for all the different combinations of variables considered for the high frequency analysis.

fore, factor 4 is indicative of high organic carbon content together with low oxygen bottom content.

Summarizing, oxic and more or less poorly oxygenated assemblages (A and C) are recorded all along the section; assemblage B, indicative of bottom stressed conditions is scattered, being essentially well represented at the base and at the top of the section. Assemblage D is recorded only from 35 m upwards.

In open marine environments, the oxygen content decreases below the photic zone up to about 1000 m, mostly due to respiration by organisms and oxidation of organic matter (Sen Gupta & Machain-Castillo 1993). This interval, the Oxygen Minimum Zone (OMZ), occurs on the continental margins of the oceans. According to Sen Gupta & Machain-Castillo (1993), an assemblage typical of bathyal OMZ is characterized by low-diversity and high dominance of few species, in particular belonging to the genera *Bolivina, Bulimina, Globobulimina, Uvigerina* and *Cassidulina*. These genera are recorded as abundant all along the Blue Clay Formation, even if they never display continuous high dominance. In consideration of the estimated paleobathymetry of 500-600 m, we suggest that the investigated sediments were deposited near or within a (paleo) Oxygen Minimum Zone environment.

Paleoceanography

High-frequency analysis

The chronological time framework obtained by Sprovieri et al. (2002) for the studied section, represents the reference scheme to study, from a cyclostratigraphic point of view, the frequency structure characterizing all the available signals. All the percentages of the benthic species show periodic fluctuations superimposed on different long-term trends. We selected, for the cyclostratigraphic analysis, only two benthic species, *C. ungerianus* and *C. subhaidingerii*, because they show the most continuous distribution with the highest percentages throughout the section.

The power spectra for all the analyzed signals show the characteristic peaks at the periodicity of 21, 41, 100 and 400 ky, respectively (Fig. 8). To identify times and modes of response of the various signals to the astronomical forcing, cross-spectral analyses have been carried out on the ensemble of time series. Coherency values and phase lags among all the coupled combinations of the two considered benthic species, the carbonate curve (data from Sprovieri et al. 2002), the planktonic oxygen isotope curve and the *Globigerinoides* spp. signals (data from Sprovieri et al. 2002) are reported in Table 2.

The *C. ungerianus* distribution curve is phased, in all the Milankovitch frequency bands (precession, obliquity, short- and long-eccentricity), to the carbonate signals, but shows an opposite response with the insolation and the *Globigerinoides* spp. curves filtered in the same frequency bands. The same signal shows an opposite behavior compared to the *C. subhaidingerii* signal which, in turn, is coupled to the insolation and *Globigerinoides* spp. signals. The plankton oxygen isotope curve shows a phased response to the carbonate and *C. ungerianus* signals and a phase lag of a semi-cycle with the insolation curve. Using the distribution and the isotope signal of the *Globigerinoides* spp. as tracers of surface waters and the benthic distributions as indicators of bottom waters, it is possible to establish, on the basis of the obtained results, a linear response of all the components of the water column to external forcing. Moreover, the response of the planktonic isotope signal phased with that of the *C. ungerianus* abundance suggests a close relationship between surface and intermediate water masses.

Characterization of intermediate central Mediterranean water mass

Comparison between long term planktonic and benthic $\delta^{18}O$ trends suggests a very similar behaviour (Fig. 6) and a quasi-constant isotope difference of about 1-1.2‰ has been calculated throughout the succession.

Using a temperature/isotope relationship of about 4°C/δ‰, the temperature gradient between surface and deep waters can be thought to have remained quite constant throughout the succession in a range of about 5-6°C. Then, considering the 17°-19°C range of sea surface temperature, estimated by Pagani et al. (1999) for the upper Langhian-lower Serravallian mid-latitude Atlantic ocean record and correcting for the ice effect with the $\delta^{18}O_{water}$ approximation, proposed by Flower & Kennett (1993), we can indicate a deep water temperature of about 12-13°C for the central Mediterranean basin during the studied interval.

Such a result is in good agreement with the information, drawn from the ostracods assemblage, indicating absence of psycrospheric environment and stable thermospheric system for the same interval.

The combination of cyclostratigraphic results and the isotopic information allows us to reconstruct times and modes of the intermediate water formation. In particular, as previously discussed, the abundance of *C. ungerianus* in the Mediterranean intermediate waters can be related to well-oxygenated environment and consequently to well-ventilated marine systems. At present, the oxygen supply in the deep Mediterranean is due to intermediate water formation that conveys high oxygen concentration from the superficial column water interacting with the atmosphere (POEM group 1992). Considering that the cyclostratigraphic results suggest a genetic relationship between surface and intermediate water masses, we speculate that an intermediate water mass was periodically generated in the Mediterranean basin and that *C. ungerianus* is a good tracer of regular influxes of such a kind of water mass.

Conversely, *C. subhaidingerii*, considered a tracer of suboxic environmental conditions, defines an opposite trend with respect to the curve of *C. ungerianus*. Thus, intervals with *C. subhaidingerii* could reflect a sluggish intermediate water formation with less oxygenated intermediate waters.

Cross-spectral results (Tab. 2) suggest that the *C. ungerianus* abundance curve is phased with the planktonic $\delta^{18}O$ curve and both signals vary in opposition with that of *Globigerinoides* spp., which in turn is phased with the insolation curve. These results indicate that intermediate waters formed during the cooler intervals of the 21, 100 and 400 ky orbital cycles. Moreover, considering that the *Globigerinoides* spp. group consists of surficial habitat species showing the maximum abun-

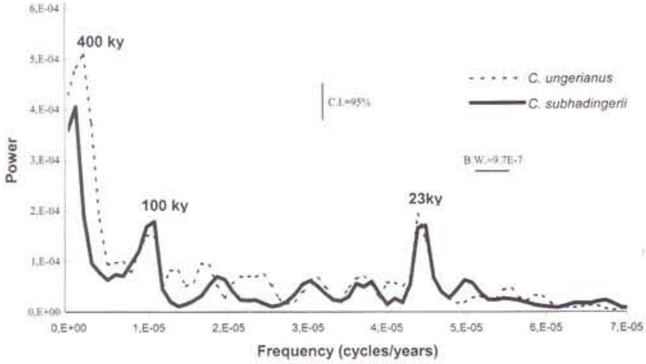

Fig. 8 - Power spectra of the *C. ungerianus* (dashed line) and *C. subhaidingerii* (thick line) curves. Confidence interval (C.I.) and bandwidth (B.W.) are reported.

dance during the spring-summer seasons (Pujol & Vergnaud-Grazzini 1995), we can speculate that winter season was the yearly period during which intermediate waters were produced. Such a result suggests that during the Langhian-Serravallian interval the intermediate water mass had similar hydrographic features and formation mechanisms to those observed for the present Levantine Intermediate Water. As for at the present, climate forcing could have been the driving mechanism for triggering excess of evaporation, loss of buoyancy of the surface waters and, consequently, intermediate water formation.

Productivity changes

The comparison between $\delta^{13}C$ values and faunal assemblages from the Ras il-Pellegrin section highlights the presence of two sedimentary intervals showing peculiar characteristics (Fig. 7).

The first interval, between 13.76 and 13.02 Ma (Fig. 3), is marked by highs in the curves of carbon isotopes, Ba concentrations and *B. costata* percentages. Concurrent high $\delta^{13}C$ values of planktonic and benthic foraminifera have been documented by Jacobs et al. (1996) for the Blue Clay Formation in a stratigraphic sequence outcropping in the Malta island, close to the Ras il-Pellegrin section. These authors suggested a correlation between the carbon positive excursion and the globally recognized Monterey C-isotope event commonly interpreted as an indicator of major perturbations of the global carbon cycle.

According to Hodell & Woodruff (1994) and Raymo (1994), the Monterey C-isotope positive excursion could be related to an increased silicate weathering, consequent to mountain building and resulting in amplified CO_2 drawdown. Vincent & Berger (1985) suggested that the registered surface productivity increase, resulted from elevated nutrient supply by river input and local upwelling changes, leading to amplified carbon production and $C_{organic}$ burial. A similar oceanographic mechanism, characterized by enhanced surface productivity due to combined effects of marginal upwelling and amplified delivery of riverine nutrients from continent to sea, could explain the C-isotope Monterey excursion recognized in the Blue Clay Formation. For our section, relatively high Ba values are consistent with intensified surface fertility and also high *B. costata* content account for the increased organic carbon burial. In accordance with Jacobs et al. (1996), the positive excursion in the benthic $\delta^{13}C$ curve is more moderate than in the oceanic records, due to the presence of an expanded minimum zone in the studied area that favored a wide availability of isotopically light CO_2 at the bottom of the basin.

The detailed sampling of our record allowed us to identify high-frequency oscillations, related to the astronomic forcing of precession and superimposed on the $\delta^{13}C$ positive general trend of the Monterey event, which testify a combined response of the sedimentary record to global climate and astronomic forcing. Furthermore, we estimated an age of about 13 Ma for the termination of the positive $\delta^{13}C$ Monterey event into the Mediterranean preannounced by a short decline in the carbon isotope curve between 13.33 and 13.18 Ma.

The second interval, between 12.84 and 12.32 Ma, is characterized by opposite trends in the planktonic and benthic $\delta^{13}C$ curves, relatively high Ba values and high percentages of *U. peregrina* (Fig. 7). Moreover, the observed benthic carbon isotope negative excursion is correlated to a negative trend in the plankton oxygen isotope curve (Fig. 7). These results implicate an increased surface productivity, possibly triggered by periodic enhanced continental runoff. The observed lightening of the benthic $\delta^{13}C$ values could represent a consequent response to the increased carbon pump effect, no more compensated by the positive carbon isotope effect of the global Monterey event, recorded in the lower part of the section. The fragmentation of the central Mediterranean area in sub-basins during the Serravallian (Meulenkamp et al. 1979; Vergnaud-Grazzini 1983; Mutti et al. 1999) could have amplified the recorded negative excursion of the benthic $\delta^{13}C$ curve, due to a sluggish thermoaline circulation system. The presence of high percentages of *U. peregrina* in this part of the section confirms the consequent enhanced preservation of organic matter at the bottom of the basin.

Reconstruction of the thermohaline circulation in the Langhian-serravallian Mediterranean

A comparison of the data obtained from the Ras il-Pellegrin composite section with isotopic and faunal results from Serravallian Western and Eastern Mediterranean sediments, suggests a simple basin-wide paleoceanographic model for the Mediterranean during the studied interval.

In particular, data on Serravallian Western Mediterranean sediments from the Balearic Basin of the DSDP Leg 42, Site 372 (Wright 1978; Benson 1978; Bizon et al. 1978) indicate a paleobathymetry of about 1000 m because the benthic microfauna was characterized by the ostracod *Agrenocythere hazelae*, indicative of psychrospheric bottom conditions (Benson 1978), together with the benthic foraminifer *Cibicidoides wuellerstorfi* and *Epistominella exigua* (Wright 1978; Bizon et al. 1978), which are typical species of deep and intermediate cool Atlantic bottom waters in the Recent (Murray 1991). These data suggest the presence in this part of the basin of psycrospheric bottom conditions and cold Atlantic waters.

Our benthic assemblage data from the Ras il-Pellegrin section suggest a persistent slightly low-oxygen bottom environment, but the ostracod assemblage, in particular the occurrence of *Oblitacythereis* spp., and the $\Delta\delta^{18}O$ bottom-surface gradient indicate the presence of thermospheric bottom water masses.

Data on benthic microfauna from Eastern Mediterranean sediments outcropping at the Tremiti Islands, indicate a paleobathymetry of about 1000 m (Russo et al. 2002), whereas abundance of the benthic foraminifer *Cibicidoides wuellerstorfi* suggests the presence of deep and cool Atlantic bottom waters. Record of the ostracod *Agrenocythere hazelae*, indicative of psychrospheric bottom conditions, which occurs only at the base of the section (Bonaduce, unpublished data; Dall'Antonia 2002), seems to support this reconstruction.

In the easternmost Mediterranean sediments from the Antalya Basin (D.S.D.P. Leg 42, Site 375, Florence Rise) more stressed conditions were registered (Hsü et al. 1978, Cita & Grignani 1982). In spite of the very poor recovery, one sapropel was recorded.

On the basis of these information, we propose a schematic basin-wide thermohaline circulation system for the late Langhian-early Serravallian Mediterranean basin. At the bottom the cold deep Atlantic waters entered the basin with consequent development of a stable psycrosphere. An intermediate water mass, probably generated in the eastern region and recorded in the central Mediterranean region (Ras il-Pellegrin section), could have represented the mass-balance outflowing mechanism. The very anoxic conditions recorded in the marginal area of easternmost Mediterranean suggest a more deficient oxygen supply to the bottom waters in these zones of the basin, probably due to slower circulation mechanisms.

Finally, as already suggested by Meulenkamp et al. (1979), Vergnaud-Grazzini (1983), and Mutti et al. (1999), the hydrographic differences recorded in the various Mediterranean areas could have been amplified by the intra-Mediterranean fragmentation tectonic phase, started in the eastern basin during the Middle Miocene as response of the closure with Indian Ocean. Such a hypothesis could explain the reduced oxygenation of bottom waters in the Alicante Province (southeastern Spain) during the Serravallian, as suggested by Gebhardt (1999).

Conclusions

The present study provides significant contributions to the faunal and geochemical dataset for the Middle Miocene Mediterranean sediments.

Cyclostratigraphic results obtained from the distribution curves of selected benthic species coupled to the plankton isotopes, carbonate, and *Globigerinoides* spp. signals suggest a direct relationship between surface and intermediate water masses during the Langhian-Serravallian in the Mediterranean basin.

Combination of isotope and benthic assemblage data allowed the characterization of such an intermediate Mediterranean water mass, characterized by hydrographic and hydrodinamic features similar to those presently recorded in the Levantine Intermediate Water.

Benthic and planktonic $\delta^{13}C$ curves, benthic foraminifer distribution and sedimentary Ba concentration indicate periodic development of relative high surface productivity, probably triggered by upwelling events combined with enhanced continental runoff. In particular, the positive carbon excursion recognized at the base of the succession has been correlated with the Miocene global C-isotope Monterey event. The detailed sampling system adopted for this study, allowed us to calibrate the termination of such an event at 13 Ma and to identify the combined astronomical and large-scale climatic forcing that produced the recorded isotope excursion.

Finally, a general thermohaline circulation system was reconstructed, that is characterized by a stable psycrosphere originated by influx of intermediate Atlantic waters below an outflowing intermediate water mass, originated in the surface central Mediterranean region.

Acknowledgements. We would like to thank E.J. Rohling for his critical comments which have improved the paper significantly. We thank also M.B. Cita and D. Violanti for reviewing an earlier version of the paper. We are grateful to E. Vecchio for the benthic foraminiferal quantitative analyses. This research has been supported by Murst Cofin 98.

REFERENCES

Benson R.H. (1978) - The paleoecology of the ostracodes of DSDP Leg 42A. In: Hsu K.J., Montadert L. et al. (eds.). *Init. Repts. DSDP*, 42: 777-783, Washington (U.S. Government Printing Office).

Bishop J.K.B. (1988) - The barite-opal-organic carbon association in oceanic particulate matter. *Nature*, 332: 341-343, Washington DC.

Bizon G., Cita M.B., Wright R & Müller C. (1978) - DSDP Leg 42 A biostratigraphic range charts. In: Hsu K.J., Montadert L. et al. (eds.). *Init. Repts. DSDP*, 42: 1095-1138, Washington (U.S. Government Printing Office).

Bizon G. & Bizon J.J. (1984) - Ecologie des foraminifères en Méditerranée nord-occidentale. Les foraminifères des sediments profond. In: Ecologie des microorganismes en Méditerranée occidentale."Ecomed". *Pétrole et Techniques*, 301: 104-139, Paris.

Boersma A.(1984) - Handbook of common Tertiary *Uvigerina*. V. of 207 pp., Microclimates press, Stony Point, New York.

Bonaduce G. & Barra D. (2002) - The ostracods in the paleoenvironmental interpretation of the late Langhian - early Serravallian section of Ras il-Pellegrin (Malta). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 211-222, Milano.

Borsetti A.M., Iaccarino S., Jorissen F.J., Poignant A., Sztrakos K., Van der Zwaan G.J & Verhallen P.J.J.M. (1986) - The Neogene development of *Uvigerina* in the Mediterranean. *Utrecht Micropal. Bull.*, 35: 183-236, Utrecht.

Calvert S.E. & Pedersen T.F. (1993) - Geochemistry of Recent oxic and anoxic marine sediments: implications for the geological record. *Mar. Geol.*, 113: 67-88, Amsterdam.

Cita M.B. (1973) - Mediterranean evaporite: paleontological arguments for a deep-basin dessication model. In: Drooger C. W. (ed.) - Messinian events in the Mediterranean. *Kon. Nedl. Akad.* Wetensch.: 206-228, Amsterdam.

Cita M.B. & Grignani D. (1982) - Nature and origin of Late Neogene Mediterranean sapropels. In: Schlanger S.O. & Cita M.B. (eds.) - Nature and Origin of Cretaceous Carbon-Rich Facies: 165-196. Academic Press, London.

Corliss B.H. (1985) - Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, 314: 435-438, Washington DC.

Corliss B.H. (1991) - Morphology and microhabitat preferences of benthic foraminifera from the Northwest Atalntic Ocean. *Mar. Micropaleontol.*, 17: 195-236, Amsterdam.

Dall'Antonia B. (2002) - Short palaeoecological notes on the middle Serravallian-basal Tortonian ostracods from the Tremiti Islands. In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 298-296, Milano.

Debono G., Xerri S. and others (1993) - Geological map of the Maltese Island; Sheet 1, Malta. Publ. by the Oil Exploration Directorate, Office of the Prime Minister, Malta. Printed by the British Geological Survey, Keyworth (C. Simpson Cartographer).

De Lange G.J., Van Os B.J.H., Pruysers P.A., Middelburg I.J., Castradori D., Van Santvoort P., Muller P.J., Eggenkamp H. & Prahl F.G. (1994) - Possible early diagenetic alteration of palaeo proxies. In: Zahn R. (ed.) - Carbon Cycling in the Glacial Ocean: Constraints on the Ocean's Role in Global Change, *NATO ASI* Ser.I, 117: 225-258, Washington.

Dyamond J., Suess E. & Lyle M. (1992) - Barium in deep-sea sediments: a geochemical proxy for paleoproductivity. *Paleoceanography*, 7: 163-181, Washington

Felix R. (1973) - Oligo-Miocene stratigraphy of Malta and Gozo. *Ph.D. thesis.* Utrecht University, Netherlands.

Flower B.P. & Kennett J.P. (1993) - Middle Miocene ocean-climate transition: High-resolution oxygen and carbon isotopic records from deep sea drilling project site 588A, southwest Pacific. *Palaeoceanography*, 8: 811-843, Washington.

Foresi L.M., Bonomo S., Caruso A., Di Stefano E., Salvatorini G. & Sprovieri R. (2002) - Calcareous plankton high resolution biostratigraphy (foraminifera and nannofossils) of the uppermost Langhian-lower Serravallian Ras Il-Pellegrin section (Malta). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 195-210, Milano.

Francois R., Nonjo S., Manganini S.J. & Ravizza G.E. (1995) - Biogenic barium fluxes to the deep sea: implication for paleoproductivity reconstruction. *Global Biogeochem. Cycles*, 9: 289-303, Washington.

Franzini M., Leoni L. & Saitta M. (1975) - Revisione di una metodologia analitica per fluorescenza X basata sulla correzione completa degli effetti di matrice. *Rend. Soc. Ital. Miner. Petrol.*, 21: 99-108, Milano.

Gebhardt H. (1999) - Middle to Upper Miocene benthonic foraminiferal palaeoecology of the Tap Marls (Alicante Province, SE Spain) and its palaeoceanographic implications. *Paleogeogr., Palaeoclimatol., Palaeecol*, 145: 141-156, Amsterdam.

Giannelli L. & Salvatorini G. (1975) - I Foraminiferi planctonici dei sedimenti terziari dell'Arcipelago maltese. I. Biostratigrafia di "Blue Clay", "Green Sands" a "Upper Globigerina Limestone". *Atti Soc. Tosc. Sci. Nat.*, Mem., Ser. A., 79: 49-74, Pisa.

Hyde H.P.T. (1955) - Geology of the Maltese Islands. V. of 135 pp., Lux Press, Malta.

Hodell D.A. & Woodruff F. (1994) - Variations in the strontium isotopic ratio of seawater during the Miocene: Stratigraphic and geochemical implications. *Paleoceanography*, 9: 405-426, Washington.

Hsu K.J., Montadert L. et al. (1978) - Sites 375 and 376: Florence Rise. *Init. Repts. DSDP*, 42: 219-304, Washington (U.S. Government Printing Office).

Iaccarino S. (1967) - Ricerche sui foraminiferi dell'alto Adriatico. *Arch. Oceanogr. Limnol.*, 15: 11-54, Venezia.

Imbrie J. & Kipp N.L. (1971) - A new micropaleontological method for quantitative paleoclimatology: application to a Late Pleistocene Carribean core. In: Turekian K.K. (ed.) - The Late Cenozoic Glacial Ages: 78-181.Yale Univ. Press., New Haven.

Jacobs E., Weissert H. & Shields G. (1996) - The Monterey event in the Mediterranean: a record from shelf sediments of Malta. *Paleoceanography*, 11: 717-728, Washington.

Jonkers H.A. (1984) - Pliocene benthonic foraminifera from homogeneous and laminated marls on Crete. *Utrecht Micropal. Bull.*, 31: 1-179, Utrecht.

Jorissen F.J. (1988) - Benthic foraminifera from the Adriatic Sea; principles of phenotypic variations. *Utrecht Micropal. Bull.*, 37: 1-174, Utrecht.

Kaiho K. (1994) - Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology*, 22: 719-722, Boulder.

Katz M. E. & Thunell R. C. (1984) - Benthic foraminiferal biofacies asssociated with middle Miocene to early Pliocene oxygen- deficient conditions in the Eastern Mediterranean. *J. Foram. Res.*, 14: 187-202, Washington.

Klovan J. E. & Imbrie J. (1971) - An algorithm and Fortran-IV program for large scale Q-mode factor analysis and calculation of factor scores. *Mathematical Geol.*, 3: 61-77, New York.

Laskar J., Joutel F. & Boudin F. (1993) - Orbital precession and insolation quantities for the Earth form -20 Myr to +10 Myr. *Astron. Astrophys.*, 270: 522-533, Washinghon.

Lohmann G.P. (1978) - Abyssal benthonic foraminifera as hydrographic indicators in the western South Atlantic Ocean. *J. Foram. Res.*, 7: 7-34, Washington.

Lutze G. F., 1986. *Uvigerina* species of the Eastern North Atlantic., *Utrecht Micropal. Bull.*, 35: 21-46, Utrecht.

Lutze G. F. & Coulbourn W. T. (1984) - Recent benthic foraminifera from the continental margin of the Northwest Africa: community structure and distribution. *Marine Micropaleont.*, 8: 361-401, Amsterdam.

Mathieu R. (1988) - Living foraminifera and upwelling on the Atlantic continental margin of Morocco. In: Benthos '86, *Rev. Paléobiol.*, vol. spec. 2: 845-850, Genève.

Meulenkamp J.E., Driever B.W.M., Jonkers H.A., Spaak P., Zachariasse W.J. & Van der Zwaan G.J. (1979) - Late Miocene-Pliocene climatic fluctuations and marine "cyclic" sedimentation patterns. *Ann. Géol. Pays Helléniques*, Hors Série II: 831-842, Athens.

Miao Q. & Thunell R.C. (1993) - Recent deep-sea benthic foraminiferal distributions in the South China and Sulu Seas. *Mar. Micropaleont.*, 22: 1-32, Amsterdam.

Miller K. G. & Lohmann G. P. (1982) - Environmental distribution of Recent benthic foraminifera on the northeastern United States continental slope. *Geol. Soc. Am. Bull.*, 93: 200-206, Boulder.

Murray J.W. (1991) - Ecology and palaeoecology of benthic foraminifera. V. of 397 pp. Longman Scientific & Technical, Harlow.

Mutti M., Bernoulli D., Spezzaferri S. & Stille P. (1999) -

Lower and middle Miocene carbonate facies in the Central Mediterranean: the impact of paleoceanography on sequence stratigraphy. *Soc. Sediment. Geol. SEPM*, Spec. Publ., 63: 371-384, Tulsa, Oklahoma.

Pagani M., Arthur M.A. and Freeman K.H. (1999) - Miocene evolution of atmospheric carbon dioxide. *Paleoceanography*, 14: 273-292, Washington.

Papp A. & Schmid M.E. (1985) - Die fossilen foraminiferen des Tertiären beckens von Wien - Revision der monographie von Alcide d'Orbigny (1846). *Abhand. Geol. Bundesanstalt*, 37: 1-311, Wien.

Passier H.F., Middelburg J.J., De Lange G.J. & Bottcher M.E. (1999) - Modes of sapropel formation in the eastern Mediterranean: some constraints based on pyrite properties. *Mar. Geol.*, 153: 199-220, Amsterdam.

Pedley H.M., House M.R., Waugh B. (1976) - The geology of Malta and Gozo. *Proc. Geol. Ass.*, 87 (3): 325-341.

Pedley H.M., House M.R., Waugh B. (1978) - The geology of the Pelagian block: the Maltese Islands. The Ocean basins and margins. In: Nairn A.E.M., Kanes W.H., Stehli F.G., (eds.) - The Western Mediterranean. Plenum Press, New York and London, 417-433, New York.

Pflum C.E. & Frerichs W.E. (1976) - Gulf of Mexico deep-water foraminifers. Cushman Found. Foram. *Res. Spec. Publ.*, 14: 1-124, Washington.

Phleger F.B., Parker F.L. & Peirson J.F. (1953) - North Atlantic foraminifera. *Repts. Swed. Deep-Sea Exped.*, 12: 1-122, Washington.

Pinardi N. & Masetti E. (1999) - Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review. *Paleogeogr., Palaeoclimatol., Palaeecol*, 158: 153-174, Amsterdam.

POEM group (1992) - General circulation of the Eastern Mediterranean. *Earth-Science Reviews*, 32: 285-309, Amsterdam.

Pujol C. & Vergnaud-Grazzini C. (1995) - Distribution patterns of live planktic foraminifers as related to regional hydrography and productive systems of the Mediterranean Sea. *Mar. Micropaleontol.*, 25: 187-215, Amsterdam.

Pujos M. (1976) - Ecologie des foraminifères benthiques et des thécamoebiens de la Gironde et au plateau continental Sud-Gascogne. Application à la connaissance du Quaternaire terminal de la région Ouest-Gironde. *Mem. Inst. Géol. Bassin d'Aquitaine*, 8: 1-274, Bordeaux.

Rathburn A.E. & Corliss B.H. (1994) - The ecology of living (stained) deep-sea benthic foraminifera from the Sulu Sea. *Paleoceanography*, 9: 87-150, Washington.

Rathburn A.E. & Miao Q. (1995) - The taphonomy of deep-sea benthic foraminifera: comparisons of living and dead assemblages from box and gravity cores taken in the Sulu Sea. *Mar. Micropaleontol.*, 25: 127-149, Amsterdam.

Raymo M. E. (1994) - The Himalayas, organic carbon burial, and climate in the Miocene. *Paleoceanography*, 9: 399-404, Washington.

Russo B., Sgarrella F. & Gaboardi S. (2002) - Benthic foraminifera as indicators of paleoecological bottom conditions in the Serravallian Tremiti sections (Eastern Mediterran, Italy). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 275-287, Milano.

Savin S.M., Douglas R.G., Keller G., Killingley J.S., Shaughmessy L., Sommer M.A., Vincent E. & Woodruff F. (1981) - Miocene benthic foraminiferal isotope records: A Synthesis. *Mar. Micropaleontol.*, 6: 423-450, Amsterdam.

Schnitker D. (1979) - The deep-water of the western North Atlantic during the past 24,000 years and re-initiation of the western boundary undercurrent. *Mar. Micropaleontol.*, 4: 265-280, Amsterdam.

Schnitker D. (1980) - Quaternary deep-sea benthic foraminifers and bottom water masses. In: Donath F.E. (ed.) - Ann. *Rev. Earth Planet. Sci.*, 8: 343-370, Amsterdam.

Schnitker D. (1994) - Deep-sea benthic foraminifers: food and bottom water masses. In: Zahn R. et al. (eds.) - Carbon cycling in the glacial Ocean: Constraints on the Ocean's Role in Global Change. *NATO ASI* series, 117: 539-554, Washington.

Sen Gupta BK. & Machain-Castillo M.L. (1993) - Benthic foraminifera in oxygen-poor habitats. *Mar. Micropaleontol.*, 20: 183- 201, Amsterdam.

Sgarrella F. & Moncharmont Zei M. (1993) - Benthic foraminifera of the Gulf of Naples (Italy): systematics and autoecology. *Boll. Soc. Paleont. It.*, 32: 145-264, Modena.

Sgarrella F., Sprovieri R., Di Stefano E., Caruso A., Sprovieri M. & Bonaduce G. (1999) - The Capo Rossello Bore-Hole (Agrigento, Sicily): Cyclostratigraphic and Paleoceanographic Reconstructions from Quantitative Analyses of the Zanclean Foraminiferal Assemblages. *Riv. It. Paleont. Strat.*, 105: 303-322, Milano.

Shackleton N.J. & Kennett J.P. (1975) - Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analysis in DSDP sites 277, 279 and 281. In: Kennett J.P., Houtz R.E. et al. (eds.). *Init. Repts. DSDP*, 23: 743-755, Washington (U.S. Government Printing Office).

Sprovieri M., Caruso A., Foresi L., Bellanca A., Neri R., Mazzola S. & Sprovieri R. (2002) - Astronomical calibration of the upper Langhian/lower Serravallian record of Ras Il-Pellegrin section (Malta Island, central Mediterranean). In: Iaccarino S.M. (ed.) - Integrated Stratigraphy and Paleoceanography of the Mediterranean Middle Miocene. *Riv. It. Paleont. Strat.*, 108: 183-193, Milano.

Streeter S.S. & Shackleton N.J. (1979) - Paleocirculation in the deep north Atlantic: 150,000 yr. record of benthic foraminifera and oxygen-18. *Science*, 203: 168-170, Washington.

Van der Zwaan G.J. (1982) - Paleoecology of Late Miocene foraminifera. Utrecht *Micropal. Bull.*, 25: 1-201, Utrecht.

Van der Zwaan G.J. & Gudjonsson L. (1986) - Middle Miocene-Pliocene stable isotope stratigraphy and paleoceanography of the Mediterranean. *Mar. Micropaleontol.*, 10: 71-90, Amsterdam.

Van der Zwaan G.J., Jorissen F.J., Verhallen P.J.J.M. & Von Daniels C.H. (1986) - *Uvigerina* from the Eastern Atlantic, North Sea Basin, Paratethys and Mediterranean. *Utrecht Micropal. Bull.*, 35: 7-20, Utercht.

Van Leeuwen R.J.W. (1986) - The distribution of *Uvigerina* in the Late Quaternary sediments of the deep eastern south Atlantic. *Utrecht Micropal. Bull.*, 35: 47-50, Utrecht.

Van Morkhoven F.P.C.M., Berggren W.A. & Edwards A.S. (1986) - Cenozoic cosmopolitan deep-water benthic foraminifera. *Bull. Centres Recherches Explor.* - Product. Elf-Aquitaine Mem.,11: 1-421, Pau.

Vergnaud-Grazzini C. (1983) - Reconstruction of Mediterranean Late Cenozoic hydrography by means of carbon isotope analyses. *Utrecht Micropal. Bull.*, 30: 25-47, Utrecht.

Vincent E. & Berger W.H. (1985) - Carbon dioxide and polar cooling in the Miocene; the Monterey hypothesis. In: Sundquist E. T. & Broecker W.S (eds.) - The Carbon Cycle and Atmospheric CO2: Natural Variations Archean to Present. *Geophys. Monogr.*, 32: 455-468, Washington.

Weedon G.P. (1991) - The spectral analysis of stratigraphic time series. In: Einsele G., Ricken W. & Seilacher A. (eds.) - Cycles and Events in Stratigraphy, Springer Verlag: 840-863, Berlin.

Woodruff F. & Savin S.M. (1991) - Mid-Miocene isotope stratigraphy in the deep-sea: high resolution correlations, paleoclimatic cycles, and sediment preservation. *Palaeoceanography*, 6: 755-806, Washington.

Wright R. (1978) - Neogene benthic foraminifers from DSDP Leg 42 A, Mediterranean Sea. In: Hsu K.J., Montadert L. et al. (eds.). *Init. Repts. DSDP*, 42: 709-726, Washington (U.S. Government Printing Office).