

Late Miocene globorotaliid event-stratigraphy and biogeography in the NE-Atlantic and Mediterranean

F.J. Sierro, J.A. Flores, J. Civis, J.A. González Delgado and G. Francés

Departamento de Geología, Facultad de Ciencias, Universidad de Salamanca, 37008 Salamanca, Spain

(Received March 28, 1991; revision accepted October 5, 1992)

ABSTRACT

Sierro, F.J., Flores, J.A., Civis, J., González Delgado, J.A. and Francés, G., 1993. Late Miocene globorotaliid event-stratigraphy and biogeography in the NE-Atlantic and Mediterranean. *Mar. Micropaleontol.*, 21: 143–168.

The quantitative study of keeled and unkeeled globorotaliids in several Late Miocene sites of the NE Atlantic, the North Betic and South Rifian Gateways and the Western Mediterranean enabled us to recognize a sequence of planktic foraminiferal (PF) events useful for a high resolution correlation of the Mediterranean with the global ocean for the time interval immediately prior to the salinity crisis.

PF-Event 1 (6.7 Ma, end of Subchron 7n1) is defined by the sudden disappearance or reduction of *Globorotalia menardii* group I (sinistral) in most of the NE Atlantic and Mediterranean. This is probably due to a southward migration of these forms to more subtropical latitudes. PF-Event 2 (6.56 Ma; Subchron 6r2) is defined by the abundant occurrence of *Globorotalia menardii* group II (dextral). Between PF-Events 1 and 2, the temperate waters of the NE Atlantic Ocean and Mediterranean Sea were almost completely lacking in keeled globorotaliids. The most prominent change in the assemblages, the replacement of the *Globorotalia menardii* group II by the *Globorotalia miotumida* group (PF-Event 3; 6.4 Ma, Subchron 6n) may be correlated with the Tortonian/Messinian boundary and is related to a widespread second southward migration of northern temperate faunas replacing the subtropical ones as the North Atlantic latitudinal thermal gradients increased. This event also coincides with the beginning of the Mediterranean crisis recorded by isotope fluctuations in surface waters and immediately followed by the development of widespread anoxic conditions in the deep and intermediate waters during the deposition of the Tripoli Formation. PF-Event 4 (first abundant occurrence of dextral specimens in the *Neogloboquadrina acostaensis* group; approximately between 5.6 and 5.5 Ma, Subchron 5r1) and PF-Event 5 (reduction or disappearance of the *Globorotalia miotumida* group; approximately between 5.6 and 5.5 Ma, Subchron 5r1) pre-date the Lower Evaporites and PF-Event 6 (First abundant occurrence of *Globorotalia margaritae* s.s.; Subchron 5n1) is contemporary to their deposition.

The coiling direction of unkeeled globorotaliids, highly variable in the first part of the Late Tortonian, became almost 100% dextral (PF-Event A) a short time after PF-Event 2. This group maintained this pattern until the Late Messinian with the exception of a short interval with a peak of sinistral forms just at the Tortonian/Messinian boundary.

On comparing these events with the carbon isotope records of different sites of the Atlantic Ocean we recognized similar trends between the events. Maximum $\delta^{13}\text{C}$ values in planktic and benthic foraminifera coincide with PF-Event 1, they decrease between PF-Events 1 and 2 and increase again immediately after PF-Event 2. PF-Event 3 coincides with the beginning of the global Late Miocene carbon shift.

Introduction

Previous contributions (Sierro, 1985; Sierro et al., 1987) recognized a series of changes in the assemblages of keeled globorotaliids in some sections of the Guadalquivir basin (Spain). Based on these studies, the present

work mainly focuses on the investigation of the geographic and stratigraphic distribution of several groups of *Globorotalia* in the NE Atlantic and the Mediterranean throughout the Late Miocene.

At present, the *Globorotalia menardii* group lives exclusively in waters from the tropical and

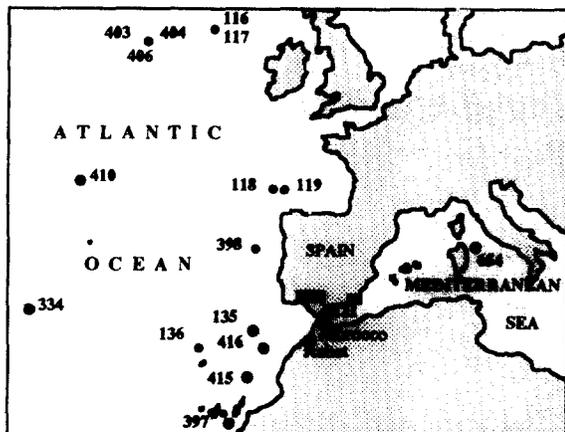


Fig. 1. Location of study area. Black areas: location of the land sections. Large circles: Sites studied in this work.

subtropical zones of the Atlantic Ocean, and has not been found northern than 30°N in the NE Atlantic Ocean, though it may be found in the NW Atlantic Ocean in latitudes more to the north, associated with the Gulf Stream flow (Cifelli, 1976; Poore, 1981).

In the North Atlantic Ocean, populations of the *G. menardii* group were abundant in the Tortonian (Beckman, 1972; Poore and Berggren, 1975; Cifelli, 1976; Poore, 1978; Cifelli and Glaçon, 1979; Salvatorini and Cita, 1979; Krasheninnikov, 1979; Salvatorini, 1979; Iaccarino and Salvatorini, 1979; Cita and Vismara Schilling, 1980; Poore, 1981; etc.). *G. menardii* has been reported at the Hatton Rockall Bank at about 50°N (Fig. 1). However, none of the authors paid special attention to the coiling direction of the populations.

Globorotalia miotumida was recognized in the North Atlantic Ocean by Feinberg and Lorenz (1970), Bossio et al. (1976), Flores and Sierro (1989) and Benson et al. (1991) in Morocco, by Sierro (1984, 1985) and Sierro et al. (1987) in Spain, by Salvatorini and Cita

(1979) and Mazzei et al. (1979) at Site 397 (Cape Bojador), by Cita and Vismara Schilling (1980) at Site 416 and by Poore (1978) at Sites 410 and 334. At all sites, *G. miotumida* appears suddenly in the late Miocene.

At Sites 403, 404 and 406 of the Hatton Rockall Bank, Krasheninnikov (1979) defined the *Globorotalia merotumida* Zone characterized by the presence of the name-giving species, *G. menardii* and *Globorotalia cultrata* and the overlying *Globorotalia plesiotumida* Zone with abundant *Globorotalia conomiozea* and *Globorotalia conoidea*.

Poore and Berggren (1975) also defined the *G. conomiozea* Zone in the upper Miocene of Site 116 in the Hatton Rockall basin and located the base of the zone at a level at which the specimens of *G. conomiozea* represented more than 50% of the plexus of *G. conoidea*–*G. conomiozea*.

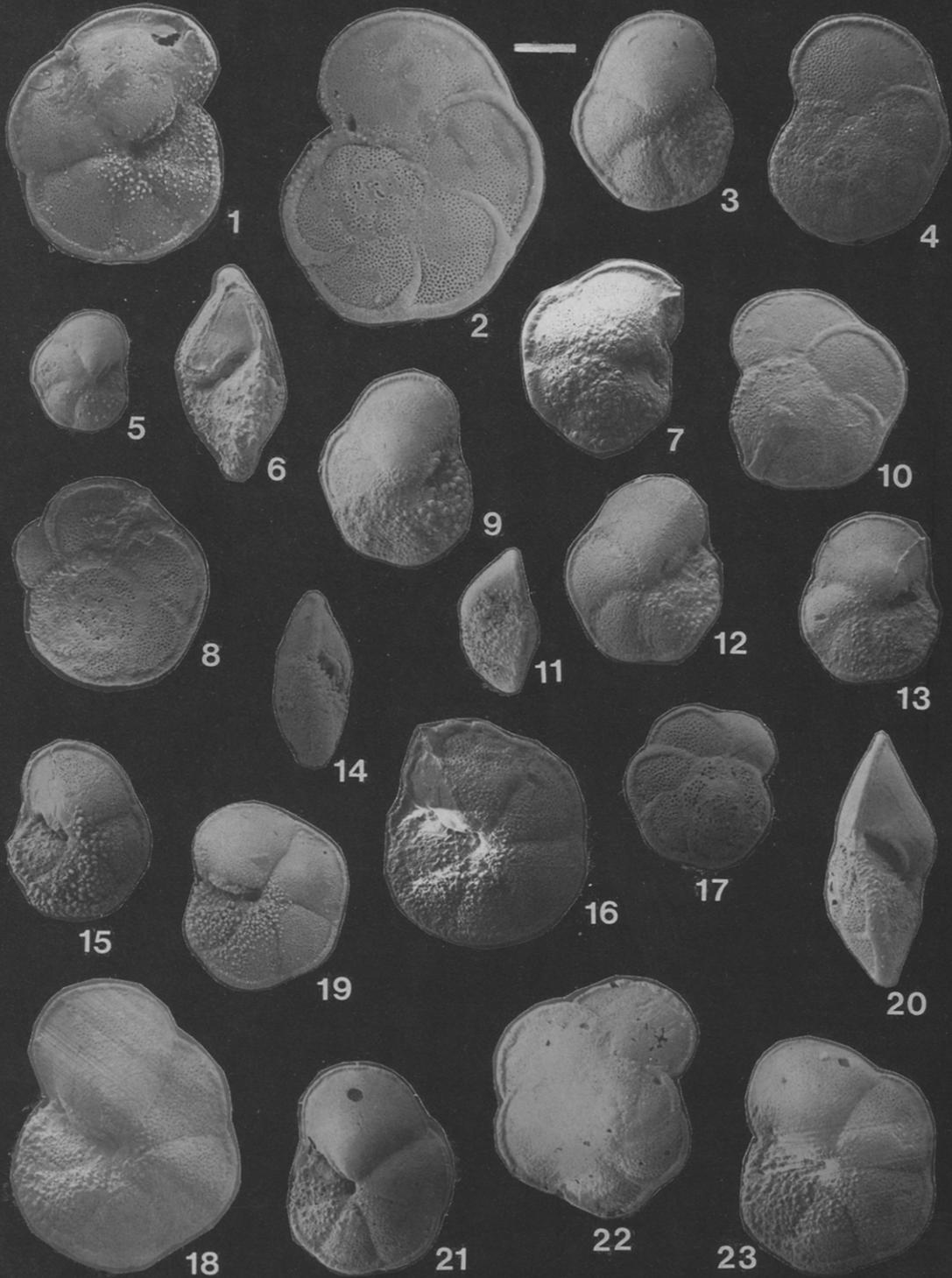
In the Mediterranean Sea several authors (D'Onofrio et al., 1975; Zachariasse, 1975, 1979; Colalongo et al., 1979; etc.) reported the sudden occurrence of convex globorotaliids such as *G. conomiozea*, *Globorotalia mediterranea* or *G. miotumida* in several Italian sections. They used this event to locate the Tortonian/Messinian boundary in the stratotype section. Sierro (1985) correlated this event in the Mediterranean with the replacement of the *G. menardii* group by the the *G. miotumida* group in the adjacent Atlantic.

Methods and materials

Almost 300 Late Miocene samples containing abundant specimens of *Globorotalia* were analyzed. All samples were wet sieved at 62, 149 and 500 μm but only the 149–500 μm fraction was analyzed. About 100 *Globorotalia*

PLATE I

Scanning electron micrographs of globorotaliids of the Late Miocene NE Atlantic. 1–8. Group I of *G. menardii* from DSDP Site 410-29/4/21-23. 9–13. Group I of *G. menardii* from DSDP Site 334-7/1/10-12. 14–18. Group II of *G. menardii* from DSDP Site 397-52/1/7-9. 19–23. Group II of *G. menardii* from the Cantillana section (Guadalquivir basin, SW Spain, Atlantic face). Sample CT-21. Scale-bar = 100 μm .



specimens were picked from each sample in order to calculate the approximate relative percentages. The majority of samples were nanofossil oozes or marly clays rich in calcareous nannoplankton and planktic foraminifera. Only in a few samples the globorotaliids were so scarce that it was necessary to use heavy liquids to separate them.

This study was based on the analysis of the associations of keeled and unkeeled globorotaliids of the following DSDP Sites of the NE Atlantic Ocean: Holes 410 (45°30.51'N; 29°28.56'W), 397 (42°50.7'N; 15°10.8'W), 334 (37°2.13'N; 34°24.87'W), 544A (33°46'N; 9°24.3'W), 135 (45°30.51'N; 29°28.56'W), 415 (31°1.72'N; 11°39.11'W) and 416A (32°50.18'N; 10°48.06'W). These results were correlated with those found in ODP Site 654 in the Mediterranean Sea. Between both realms several land-based sections were analyzed in the North Betic (south Spain) and South Rifian (north Morocco) foredeeps to the north and south of the Gibraltar Arc, respectively (Fig. 1). Both regions were very important during the Late Miocene, because they were probably the main gateways connecting the Atlantic Ocean and the Mediterranean Sea.

In the western part of the North Betic Gateway (Guadalquivir basin) complete and condensed sections of Late Miocene age are exposed. The sections of Gibralfón, Beas-Trigueros, Guillena, Cantillana and Arroyo Galapagar (lower part of the Andalusian type section) were studied, whereas in Morocco only the Oued Akrech section, situated near Rabat, was analyzed (see Fig. 1).

Taxonomic notes

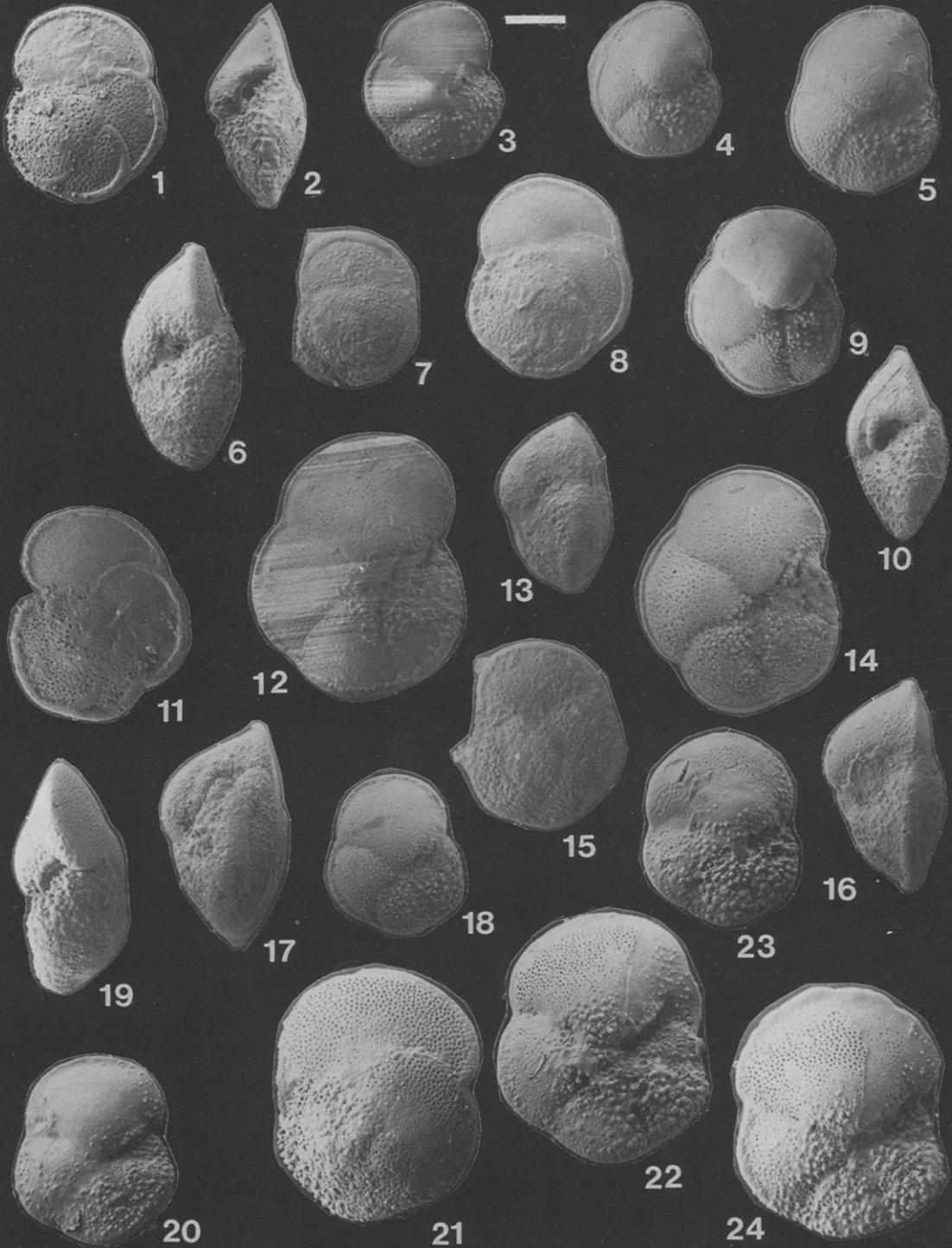
Our *G. menardii* group I is referable to *G. menardii* form 4 of Tjalsma (1971) and Zachariasse (1975). The morphology of this group is fairly variable (Plate I, 1–13). Specimens of *G. cultrata* s.s. are present in some samples but there is a predominance of specimens with tight coiling, a closed umbilicus and embraced chambers that were identified as *G. merotumida* and *G. plesiotumida*. In the dorsal view, the chambers exhibit a more or less reniform periphery and rapid expansion, whereas the ventral side is relatively inflated. Some of these specimens are similar to *G. miotumida* though they do not exhibit the high arched aperture characteristic of this species. Zachariasse (1975) also noted the existence of specimens with a highly inflated umbilical side, even resembling *G. conomiozea*. The coiling direction of this group is preferentially sinistral.

G. menardii group II has more open spire and umbilicus, with relatively low ventral convexity (Plate I, 14–23). The dorsal view shows a more or less rapid growth and a semicircular periphery. The specimens of *G. cultrata* or *Globorotalia limbata* are dominant, while *G. plesiotumida* and *G. merotumida* may also be present. This group is preferentially dextral and is similar to *G. menardii* form 5 of Tjalsma (1971) and Zachariasse (1975). We use the same taxonomic criteria to recognize both groups, because we believe that the morphologic difference between the two is related to ecophenotypic variations, as may be deduced by analyzing the morphological changes in a single group related to latitude.

The *G. miotumida* group (Plate II, 1–18)

PLATE II

Scanning electron micrographs of globorotaliids of the Late Miocene NE Atlantic and Mediterranean. 1–3. *Globorotalia miotumida* group from the Cantillana section (Guadalquivir basin, SW Spain, Atlantic face). Sample CT-27. 4–8. *Globorotalia miotumida* group from DSDP Site 410-23/3/65-67. 9–12. *Globorotalia miotumida* group from the Arroyo Galapagar section (Guadalquivir basin, SW Spain, Atlantic face). Sample AR-23. 13–18. *Globorotalia miotumida* from the Arejos section (Sorbas basin, SE Spain, Mediterranean). Sample CME-90. 19–24. *G. margaritae* from DSDP Site 397-41/7/18-20. Scale-bar = 100 μ m.



consists of several species with a very characteristic planoconvex periphery in lateral view and with different levels of convexity of the umbilical side. It includes *G. miotumida*, *G. conoidea* (probably a deep ecophenotype of *G. miotumida*), *G. mediterranea* and *G. conomiozea* (as used in the Mediterranean Sea). The abundance of each one of these species is different, depending on the region studied.

According to the aforementioned criteria we can relate the *G. menardii* groups I and II with the *Globorotalia tumida* and *Menardella* groups of Srinivasan and Kennett (1981) and the *G. miotumida* group with the *Globoconella* group of the same authors.

The *Globorotalia scitula* group, consisting of *G. scitula*, *Globorotalia ventriosa* s.l. and *Globorotalia suterae*, also exhibit morphologic

variations and changes in the coiling direction which can be used for regional correlations.

Planktic foraminifera events

In all the sections analyzed a quantitative study of the *Globorotalia* specimens was performed to find the relative abundance of the different groups of the genus throughout the Late Miocene. Moreover, the sinistral and dextral specimens of the *G. scitula* group were counted in order to recognize the main changes in the group. The results of these analyses are shown in Figs. 2 to 11, where the main quantitative or qualitative changes in the assemblages are identified as PF-Events 1 to 6 and PF-Event A.

PF-Event 1 is defined by the sudden disap-

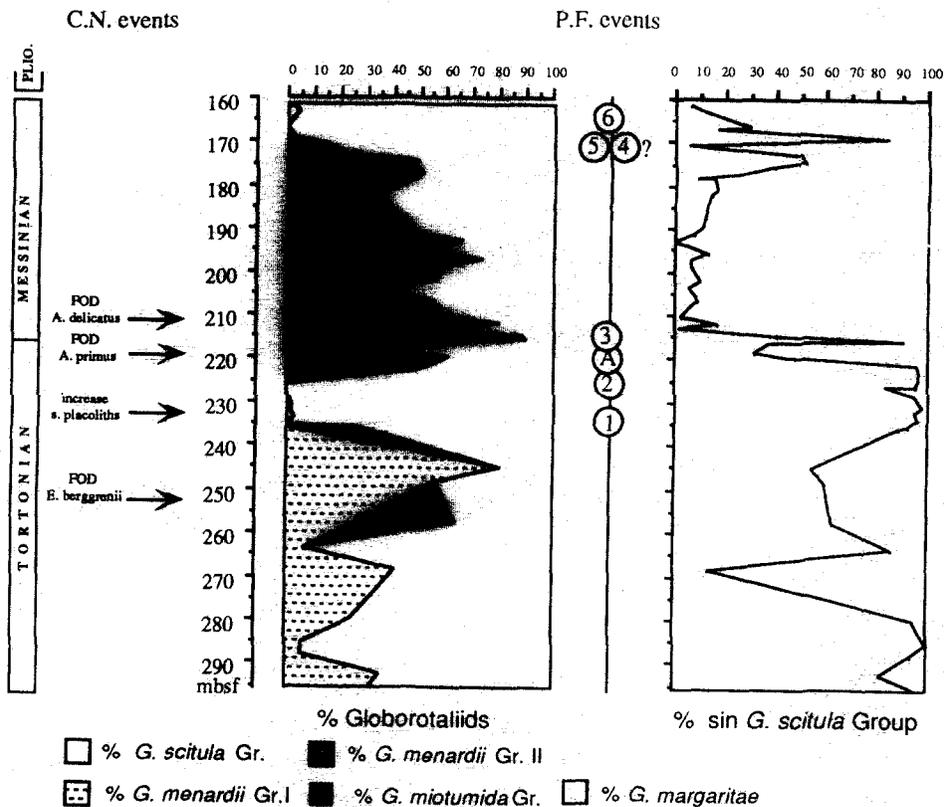


Fig. 2. Variation in the assemblages of globorotaliids in DSDP Site 410 and location of the main calcareous nannoplankton (CN) and planktic foraminifera (PF) events from bottom to top. Only globorotaliids were taken into account for this analysis in order to calculate the relative abundance among them. The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

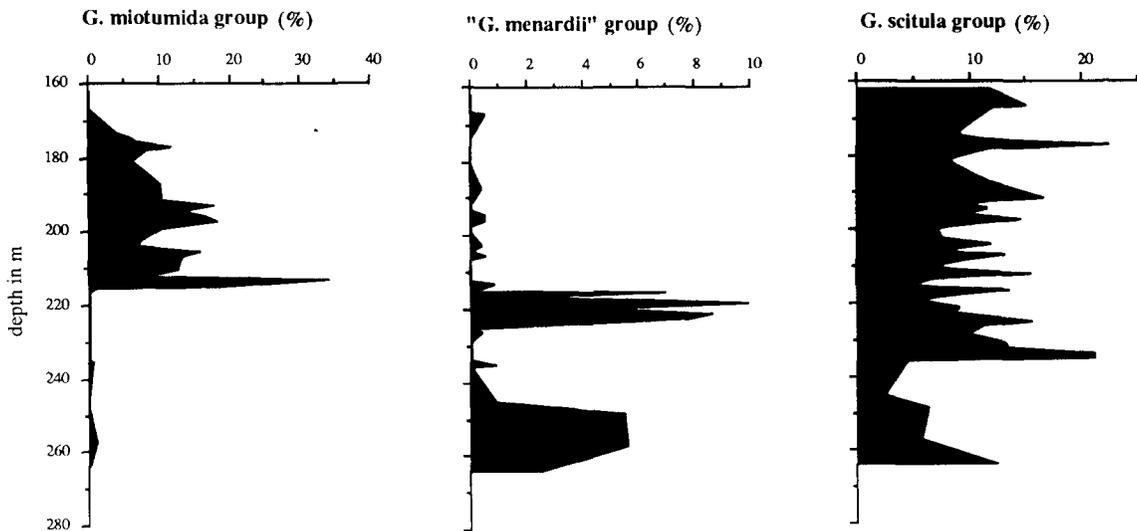


Fig. 3. Relative abundance of the different groups of *Globorotalia* taking into account the whole planktic foraminiferal association of DSDP Site 410.

pearance or reduction of the *G. menardii* group I (see Figs. 2, 5, 8, 9 and 11). It was clearly found at Site 410, in Morocco and in all the Guadalquivir basin sections, always coinciding with a strong increase in the small placoliths in the calcareous nannoplankton assemblage (Flores and Sierro, 1989). At Site 334 the specimens of the *G. menardii* group I are abundant up to 163 mbsf (meters below seafloor; Fig. 5). At this level a reduction occurs in this group and the unkeeled globorotaliids become dominant. However, in this interval forms with a strong ventral convexity which are strongly encrusted are present. The difference between these forms and those existing above 142 mbsf corresponding to the typical forms of *G. miotumida* s.s. is apparent. The approximate coincidence of the strong reduction of *G. menardii* group I with the increase in small placoliths recorded in other areas suggests that this coccolith event may be correlated with PF-Event 1.

The location of PF-Event 1 at Site 397 is very problematic, because *G. menardii* group I is abundant until it is replaced by group II at 498 mbsf (Fig. 4). At this site the interval in which the keeled globorotaliids are absent or poorly

represented has not been found. The evident preference of this group for subtropical waters probably explains its continuous presence at this latitude, whereas in more northerly areas (Morocco, Spain, Site 410, etc.) the group reduces its abundance or disappears. However, upon analyzing the calcareous nannoplankton, an increase was seen in the small placoliths between 505 and 515 mbsf (Flores and Sierro, 1989) which can be correlated with that found in other regions.

PF-Event 2 is defined by the sudden abundant occurrence of group II of *G. menardii* after an interval in which keeled globorotaliids are very reduced or absent. It can easily be identified at Sites 410 and 397, in Spain and Morocco and was also found by one of us in the Tyrrhenian Sea (Glaçon et al., 1990; Figs. 2, 4, 8, 9 and 11). This event is always located between the increase in small placoliths and the FOD (first occurrence datum) of *Amaurolithus primus* (Flores and Sierro, 1989; Flores et al., in press).

At Site 334, according to our data, PF-Event 2 coincides with a hiatus between 142 and 149 mbsf (Fig. 5), which is marked by a sharp change in the association of keeled globorota-

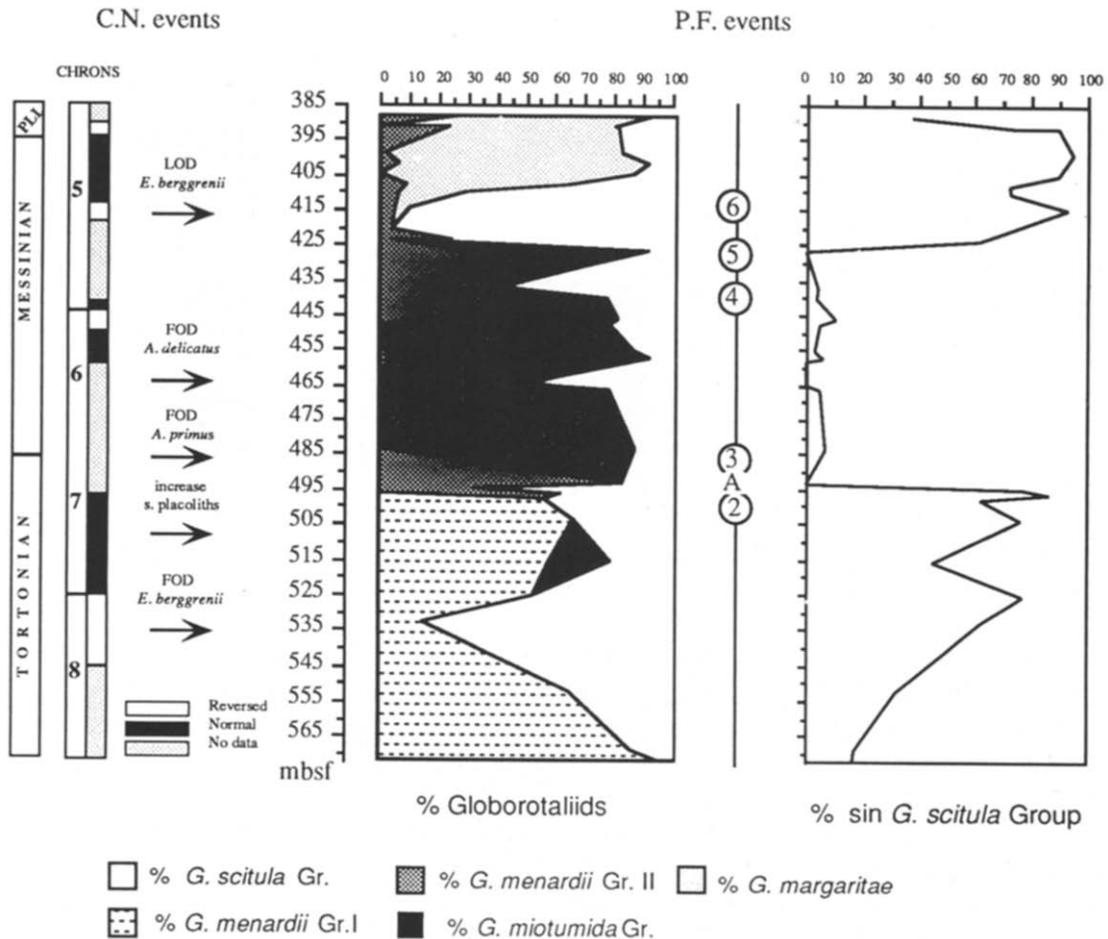


Fig. 4. Variation in the assemblages of globorotaliids in DSDP Site 397. Paleomagnetic data from Hamilton (1979). The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

liids, since—although the *G. miotumida* group is dominant during a longer interval—above 142 mbsf only specimens of *G. miotumida* occur, while below this level there is a predominance of *G. conoidea*. The forms of the *G. menardii* group also disappear from that horizon on. Another very significant aspect that supports the existence of a hiatus at this level is the coincidence of PF-Events 3 and A and the disappearance in the upper cores of siliceous microfossils (radiolarians and diatoms) that are relatively frequent in the lower part of the section.

PF-Event A is defined by a coiling change from sinistral to dextral in the *G. scitula* group which approximately coincides with the FOD

of *A. primus* in all the sections analyzed both in the NE Atlantic Ocean and in the Mediterranean Sea (Sites 410, 397 and 334, in Spain, Morocco and the Tyrrhenian Sea; Figs. 2, 4, 5, 8, 9 and 11).

PF-Event 3, characterized by the replacement of the *G. menardii* group II by the *G. miotumida* group, is a prominent change in all the sections (Sites 410 and 397, Guadalquivir, Sorbas and South Rifian basins; Figs. 2, 4, 8, 9, 10 and 11). In all these sections, this event is recorded slightly above the FOD of *A. primus*. In Fig. 4 both events appear together, because they occur in an interval of almost 9 m of no recovery. In the Tyrrhenian Sea one of us (in Glaçon et al., 1990) placed PF-Event 3 at

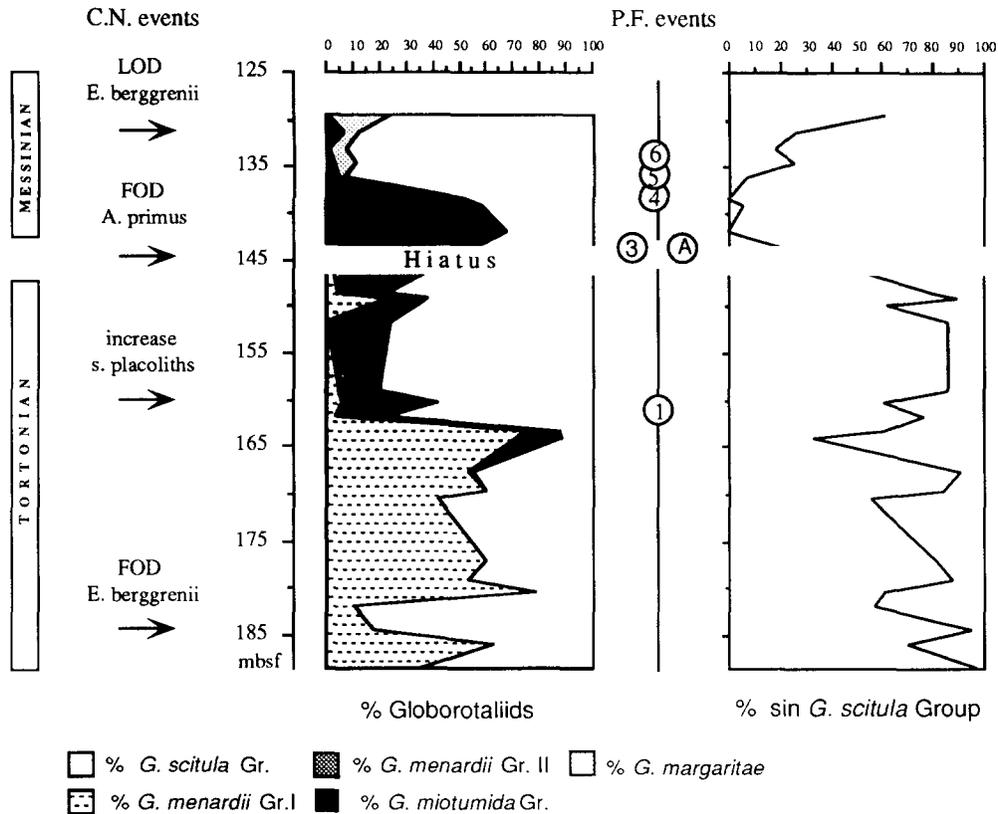


Fig. 5. Variation in the assemblages of globorotaliids in DSDP Site 334. The white area shows the relative abundance of the unkeeled globorotaliids=*G. scitula* group.

the level of the first abundant occurrence of the *G. miotumida* group, because at Site 654 the replacement of the *G. menardii* was not observed, since this group is absent from at least 1 m below that event. The FOD of *G. conomiozea*, traditionally used to locate the Tortonian/Messinian boundary in the Mediterranean Sea, occurred 1 m above PF-Event 3. The *G. miotumida* group is not dominated by this species, since the more convex forms, such as *G. conomiozea* or *G. mediterranea*, are usually very abundant. In the Sorbas basin (Spain), another characteristic Western Mediterranean region, *G. menardii* group II seems to disappear prior to the entry of the *G. miotumida* group (see Fig. 10). Both events took place approximately several meters below the deposition of the first white laminated marlstones (see p. 157). In this section we observed strong

abundance variations within the *G. miotumida* group. At the lower levels *G. miotumida* is the dominant species, as in the Tyrrhenian Sea, but in the middle part the specimens exhibit a large ventral convexity and a strongly pustulose wall, typical of *G. conoidea* and *G. conomiozea* as used in the Mediterranean Sea.

PF-Event 4, the only one not related to *Globorotalia* assemblages, is defined by the first common occurrence of dextral forms in the *N. acostaensis* group after a long period of dominance of the sinistrally coiled specimens (over 90%; Figs. 2, 4, 5, 6, 8 and 10). This event was found in all the sites studied, but its accurate location is not easy to determine, because in some places there are several sinistral to dextral oscillations until the group becomes definitely dextral. In the sites analyzed in this study it usually occurs prior to PF-Event 5 (Sites 397,

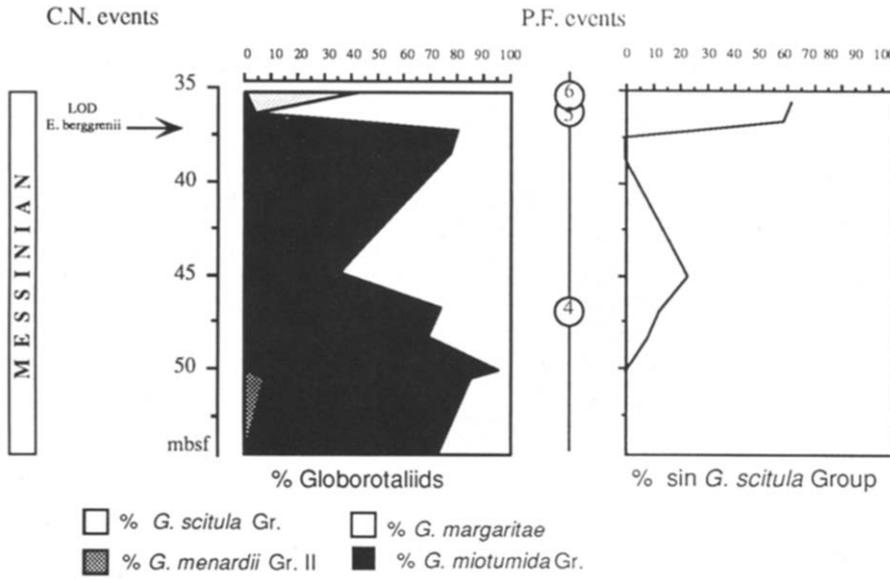


Fig. 6. Variation in the assemblages of globorotaliids in DSDP Site 544A. The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

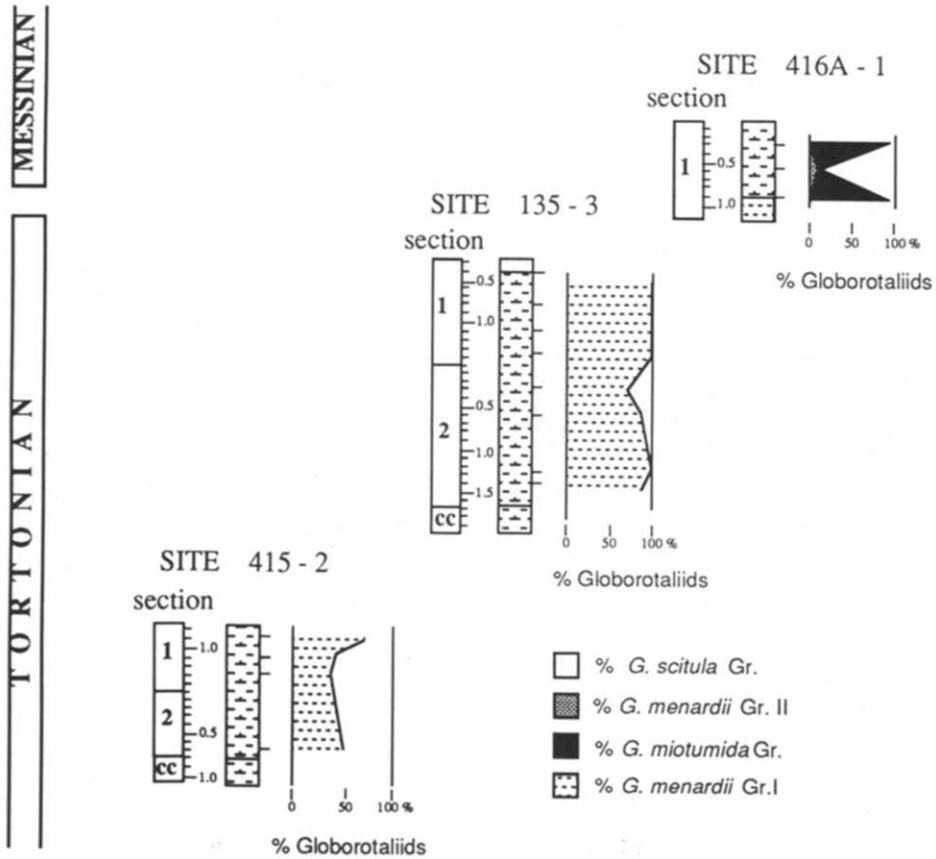


Fig. 7. Variation in the assemblages of globorotaliids in DSDP Sites 415, 135 and 416. The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

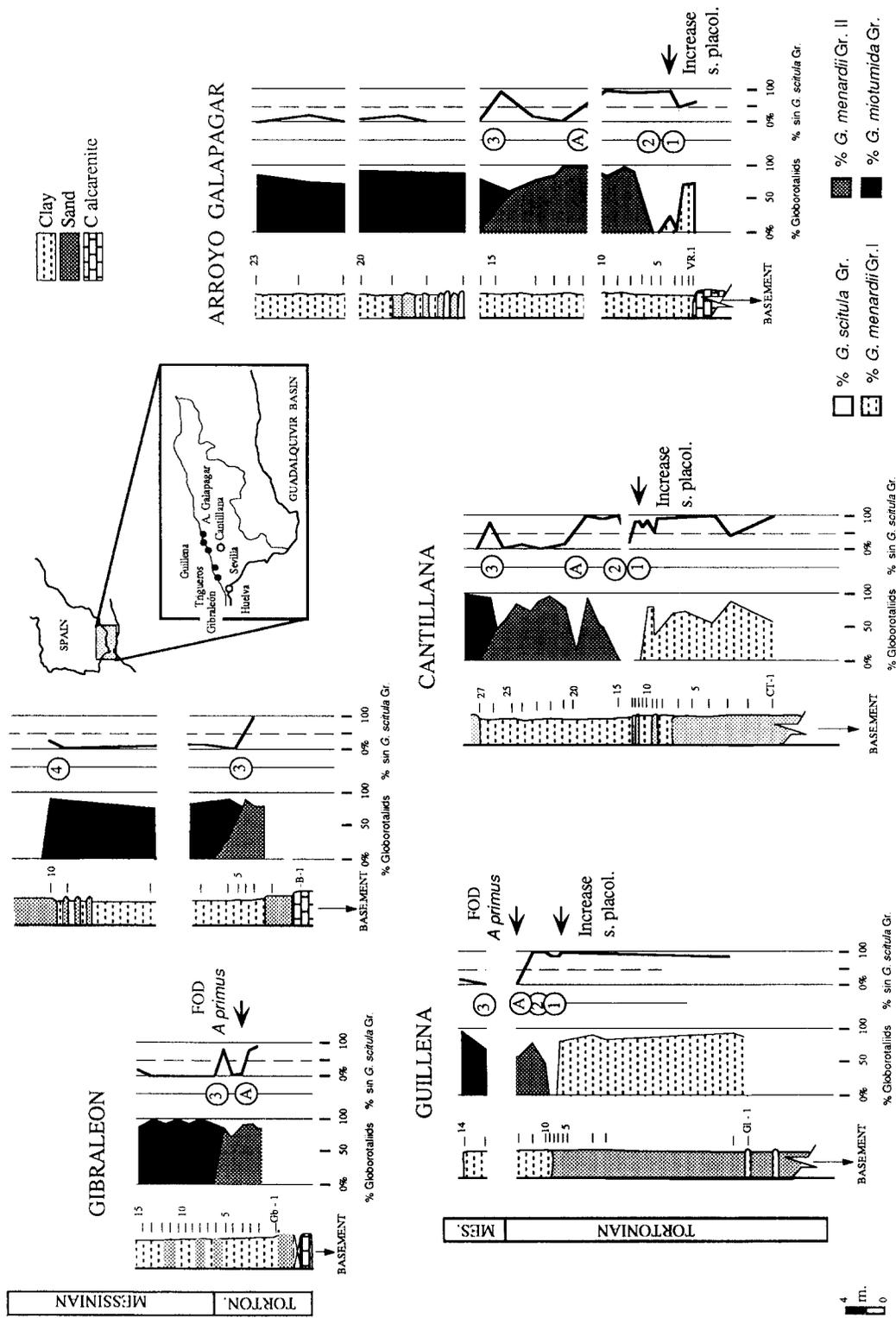


Fig. 8. Variation in the assemblages of globorotaliids in 5 sections of the Guadalquivir basin. Modified from Sierro et al. (1987). The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

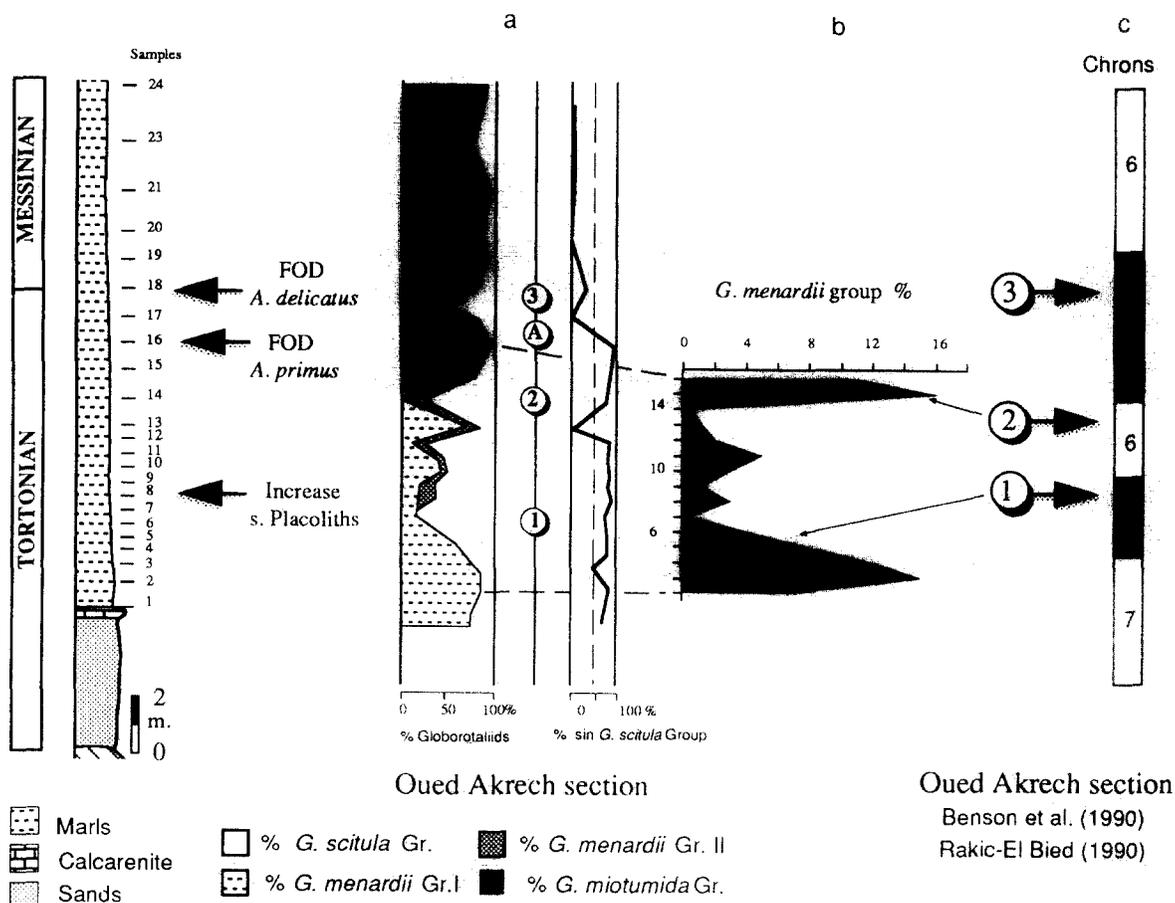


Fig. 9. (a) Variation in the assemblages of globorotaliids in the Oued Akrech Section (South Rifian basin, Morocco). (b) Relative abundance of the *Globorotalia menardii* groups I and II in the planktic foraminifera association. (c) Location of PF-Events 1 to 3 in the magnetostratigraphic scale after Benson et al. (1991) and Rakic-El Bied (1990). The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

334 and 544A and in the Guadalquivir basin) or coinciding with it (Site 410). In the Sorbas basin, this event was recognized just below the Lower Evaporites.

PF-Event 5 is characterized by a sharp decrease or disappearance of the *G. miotumida* group which up to this time was dominant among the globorotaliids (Sites 410, 397, 334 and 544A; Figs. 2, 4, 5 and 6).

After PF-Event 5, during the Late Messinian when the keeled globorotaliids were very poorly represented in the NE Atlantic, *Globorotalia margaritae* s.s. became a common taxon in the assemblages of keeled *Globorotalia*. This, referred to as PF-Event 6, is more easily located

in the sections than the FOD of *G. margaritae*, because of the taxonomical problems related to its identification near the evolutionary transition from its ancestor. In many sections we have found specimens very close to *G. margaritae* throughout the Messinian, but either without a well developed keel or with a dextral coiling. PF-Event 6 was identified to occur immediately above PF-Event 5 at Sites 397, 334, 544A and 410 in the NE Atlantic (Figs. 2, 4, 5 and 6).

An additional useful stratigraphic tool is found in the coiling direction of the *G. scitula* group (Fig. 12). In all the sections we can deduce that after PF-Event A the group keeps its

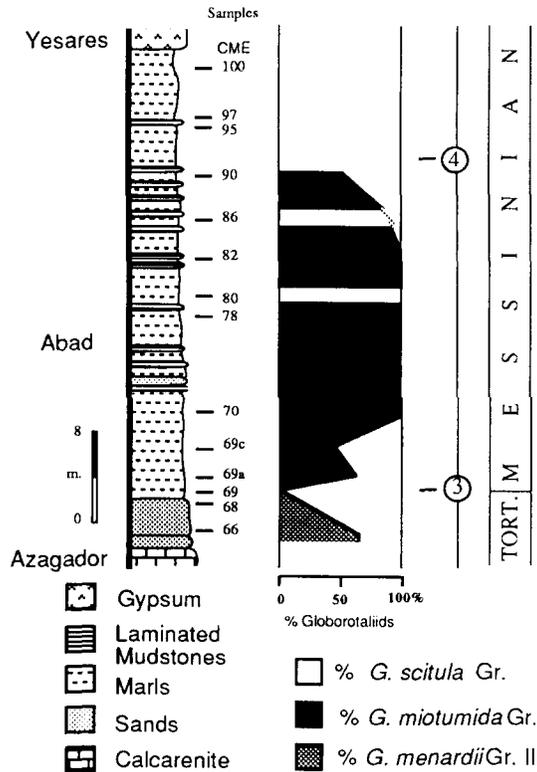


Fig. 10. Variation in the assemblages of globorotaliids in the Rambla de Arejos section (Sorbas basin, SE Spain). The white area shows the relative abundance of the unkeeled globorotaliids = *G. scitula* group.

preferentially dextral coiling during the interval in which the *G. miotumida* group is abundant in the NE Atlantic with the exception of a strong peak of sinistral forms coinciding with PF-Event 3 (PF-Events B and C defined by the dextral to sinistral and sinistral to dextral changes, respectively). This peak may be observed in all sections in which there is a high resolution sampling of this interval as, for example, at Site 410 or in the sections of the Guadalquivir basin (Figs. 2 and 8, respectively). At Site 654 a dextral to sinistral change (PF-Event B) in the *G. scitula* group was found by one of us just below PF-Event 3 (Glaçon et al., 1990), which could be correlated with this peak in the adjacent Atlantic Ocean. At this site above this level the *G. scitula* group is so scarce that it was not possible to analyze its coiling,

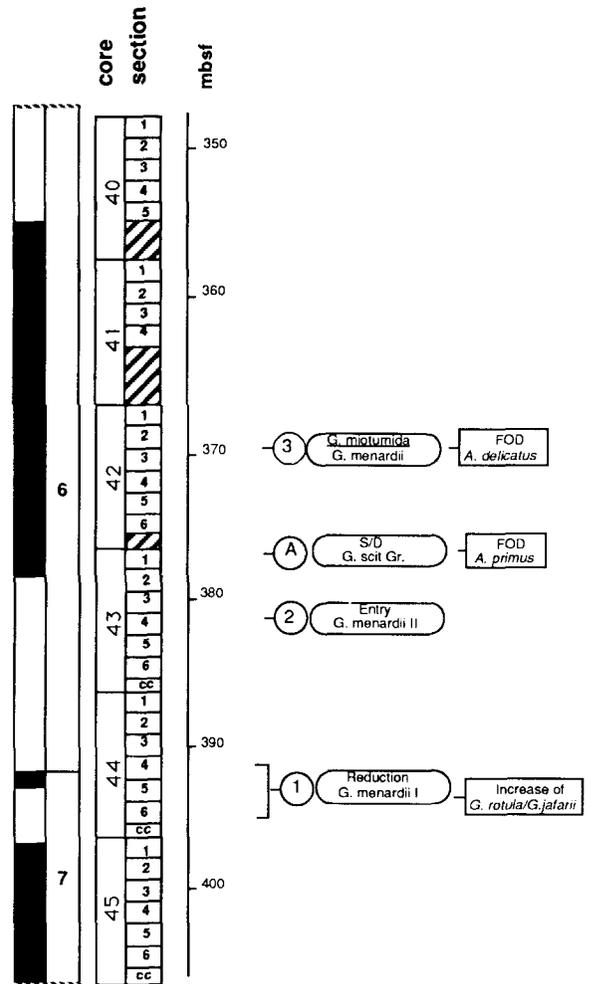


Fig. 11. Location of the main planktic foraminifera and calcareous nannoplankton events in ODP Site 654 (Tyrrhenian Sea). Magnetostratigraphic data according to Channell et al. (1990).

but in the Arejos section, the group again becomes dextral (PF-Event C) after PF-Event 3. During the late Messinian, between PF-Events 4 and 5 the group again becomes progressively sinistral (PF-Event D) as may be seen in Figs. 2, 4, 5 and 6. Therefore, we suggest the existence of a similar pattern in coiling changes throughout the Late Miocene in the region studied, which may be useful for Atlantic-Mediterranean stratigraphic correlation.

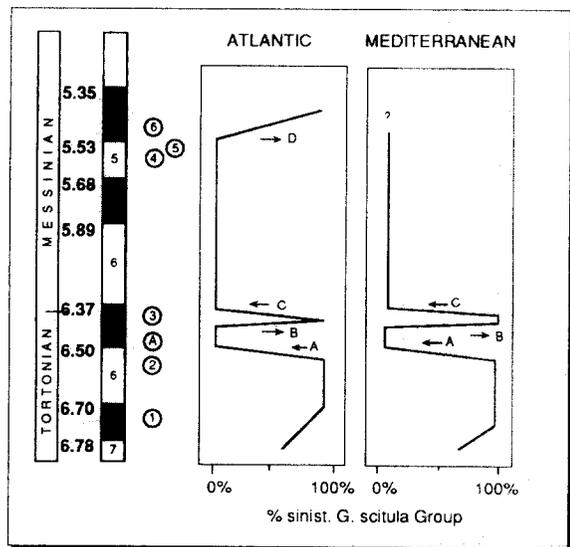


Fig. 12. Schematic graph showing the coiling trend of the *G. scitula* group in the North Atlantic and Mediterranean. Tentatively PF-Events A, B, C and D are proposed to characterize the main changes in coiling direction.

Correlation of the bioevents with magnetostratigraphy and stable isotope stratigraphy

The correlation of the calcareous plankton events with the magnetostratigraphic scale was possible both in the Tyrrhenian Sea and Morocco, based on data from Channell et al. (1990) and Benson et al. (1991), respectively.

As may be seen in Fig. 11, PF-Event 1 in the Tyrrhenian Sea was recorded during an interval ranging from immediately below to immediately above Subchron 7n1, PF-Event 2 lies within the upper part of Subchron 6r2, PF-Event A in the basal part of Subchron 6n1, whereas PF-Event 3 is located towards the middle part of this Subchron.

In Morocco, Benson et al. (1991) and Rakic-El Bied (1990) studied two cored wells in Ain el Beida and Salé and the Oued Akrech sections in the South Rifian basin, and found the same sequence of events that were correlated to the magnetostratigraphic scale (Fig. 9). According to their data, PF-Event 1 was located in the upper part of Subchron 7n1. PF-Event 2 lies in the upper part of Subchron 6r2 and PF-

Event 3 coincides with the upper part of Subchron 6n1. PF-Event A was not identified by these authors.

Our data do not support either the paleomagnetic interpretation of Kastens and Mascle (1990) for ODP Site 654, or the interpretation of Langereis et al. (1984) for Late Miocene sediments of Crete. The main line of argument against their interpretation are the following: (1) The FOD of *A. primus* is a very useful stratigraphic datum globally related to Subchron 6n1 (Haq et al., 1980) and, consequently, PF-Event 3, recorded immediately after the FOD of *A. primus*, must be correlated with this subchron and not with Subchron 5n2, as suggested by Langereis et al. (1984) and Kastens and Mascle (1990). (2) The carbon shift recorded by Glaçon et al. (1990) at Site 654 and used by Kastens and Mascle (1990) in favor of their paleomagnetic interpretation is not the same as the one found in the global ocean and thus it cannot be used in the stratigraphic correlation (see below). (3) Therefore, the global carbon shift, generally correlated with Subchron 6n1, is approximately contemporaneous with PF-Event 3.

All these data are in favor of the paleomagnetic interpretations of Channell et al. (1990) for Site 654 and Berggren et al. (1985; see also Hsü, 1985 and Moreau et al., 1985) for Crete and are therefore followed in this study.

PF-Event 1 (decrease *G. menardii* group I) may be correlated with the LOD of *G. menardii* form 4 identified by Langereis et al. (1984) in Crete. This event was located only in the Skouloudhiana section within Subchron 7r1 according to the reinterpretation of Berggren et al. (1985). The correlation of this event in relation to the magnetostratigraphic data is not very accurate because in Morocco it seems to lie within Subchron 7n1, whereas in Crete it seems to be slightly older. However, we take the data of Morocco as more reliable because in the Mediterranean Sea the keeled globorotaliids are generally scarce and therefore their

disappearance is more difficult to determine correctly.

PF-Event 2 (abundance increase of *G. menardii* group II) coincides with the entry of *G. menardii* form 5 identified by Langereis et al. (1984) in the upper part of Subchron 6r2, strongly coinciding with its location both in Morocco and the Tyrrhenian Sea. The replacement of the *G. menardii* group by the *G. miotumida* group in the Atlantic Ocean must be related to the event literally described by Langereis et al. (1984, p. 265) in Crete as "the abrupt and instantaneous recurrence of sinistrally keeled globorotaliids above the FOD of *G. menardii* form 5". This event was found in sections Potamida 1 and 3 in the middle part of Subchron 6n1, which coincides well with its occurrence in Morocco and the Tyrrhenian Sea.

After establishing the magnetostratigraphic correlation among Morocco, Site 654 and Crete we can estimate an age of approximately 6.7 Ma for PF-Event 1 and 6.56, 6.48 and 6.4 Ma for PF-Events 2, A and 3, respectively, according to the geochronologic time scale of Berggren et al. (1985).

Langereis et al. (1984) recorded the FOD of *G. conomiozea* during Subchron 6r1 which leads us to suggest that this event may be slightly diachronous because at Site 654 this species occurred from the middle part of Subchron 6n1.

The accuracy of the correlation between our events and the classic biostratigraphical zones of the Mediterranean Sea is not good, but we tentatively correlate the boundary between subzones of *Globigerinoides obliquus extremus* and *G. suterae* of D'Onofrio et al. (1975) between PF-Events 1 and 2.

PF-Event 3 (replacement of *G. menardii* group II by *G. miotumida* group) is contemporary with the first evidence of the Mediterranean crisis. Coinciding approximately with this event, there was an important reduction in the diversity of benthic communities, as observed by Colalongo et al. (1979) in the Falconara section in Sicily. This was probably re-

lated to a strong change in deep-water circulation. Moreover, immediately above this event, the Tripoli Formation in Sicily, the dolomites in the Tyrrhenian Sea and the intermittent white laminated marlstones in the sections of Arejos (Sorbas basin, Spain) and Potamida (Crete) began to be deposited, showing that at this time anoxic bottom conditions are widespread in deep and intermediate waters of the Mediterranean Sea (Fig. 13). The water stratification seems to occur constantly in deep Mediterranean environments during the Early Messinian (Falconara section and Tyrrhenian Sea), whereas a cyclical alternation between oxygenated and anoxic conditions occurs in intermediate waters (Crete, Sorbas). The development of anoxic conditions may be dated 6.3 Ma at Site 654 in the Tyrrhenian Sea. At this site, coinciding with PF-Event 3, high but fluctuating $\delta^{18}\text{O}$ values were recorded by Glaçon et al. (1990) indicating strong fluctuations in the salinity of surface waters. A similar $\delta^{18}\text{O}$ increase was observed by Vergnaud Grazzini (1983a) below the Tripoli Formation in the Monte Giammoia section (Sicily).

PF-Event 4 (change to dextral coiling in *N. acostaensis* group) has been widely recognized both in the Atlantic Ocean and the Mediterranean Sea (Stainforth et al., 1975; Zachariasse, 1975; Bossio et al., 1976; Montenat et al., 1976; Manuputti, 1977; Gonzalez Donoso and Serano, 1977b; Colalongo et al., 1979; Mazzei et al., 1979; Salvatorini and Cita, 1979; Civis et al., 1979; Van der Zwaan, 1982; Langereis et al., 1984; Hooper and Weaver, 1987; Benson et al., 1991; Benson and Rakic-El Bied, 1991; etc.). Hooper and Weaver (1987) found a first peak of dextral forms in the *N. acostaensis* group in several DSDP Sites of the North Atlantic. At Site 609 this peak was located in the middle part of Subchron 5r1. In Morocco, according to Benson et al. (1991) this event lies on top of Subchron 5r whereas in Crete, according to Langereis et al. (1984), it lies above the youngest sediments analyzed and, hence,

this event probably took place during Subchron 5r1 or 5n1. However, a quantitative study of this group and a high resolution stratigraphy is necessary to be sure that we are comparing the same event in all these sites.

PF-Event 5 (disappearance of *G. miotumida* group) appears to be caused by the disappearance of the *G. conoidea* group recorded by Hooper and Weaver (1987) at Site 609 (North Atlantic) during Subchron 5r1. However, at that site, in contrast to our observations, this event took place immediately prior to PF-Event 4. At any rate, both events seem to be related to Subchron 5r1 with an estimated age between 5.5 and 5.6 Ma.

The change from sinistral to dextral in the *N. acostaensis* group (PF-Event 4) has been recorded in the Mediterranean Sea just below the Lower Evaporites by Stainforth et al. (1975), Manuputti (1977), Civis et al. (1979), Benson and Rakic-El Bied (1991), and others. In Falconara PF-Event 5 is caused by the disappearance of *G. conomiozea* and lies in the upper part of the Tripoli Formation just below the "Calcare di base" and the Lower Evaporites. There and in the Arejos section studied in this work and in the Cuevas de Almanzora section (SE Spain) (Montenat et al., 1977; Gonzalez Donoso and Serrano, 1977b; Civis et al., 1979; Benson and Rakic-El Bied, 1991; etc.) PF-Events 4 and 5 thus seem to coincide. In all these regions both events approximately coincide with the boundary between the subzones of *G. mediterranea* and *G. multiloba* defined by D'Onofrio et al. (1975) by the FOD of *G. multiloba* and characterized by a strong reduction in the diversity of the planktic and benthic foraminiferal assemblages.

Recently one of us (F.J. Sierro, unpubl. data) has located PF-Event 4 in the Fortuna basin (SE Spain) approximately coinciding with the deposition of the lower Mamoya marls at Fortuna (Event 1) of Müller and Hsü (1987; Fig. 13). The Tortonian/Messinian boundary and consequently PF-Event 3 has not been identified, but it could be located at the base of

the Mamoya marl (see Luckowski et al., 1988), as may be deduced by correlation with the Arejos section and other late Miocene transgressive sequences in several basins in Southeast Spain.

Up to last year *G. margaritae* had never been recognized in the Mediterranean Sea before the Pliocene, leading us to suggest that its FOD would have taken place during the deposition of the Lower Evaporites. But recently, Benson and Rakic-El Bied (1991) reinterpreting data from Montenat et al. (1976) of the Cuevas de Almanzora section (Sorbas basin), have pointed out the continuous record of the sinistral to dextral change in *N. acostaensis*, the LOD (last occurrence datum) of *G. mediterranea* and the FOD of *G. margaritae* during Subchron 5r1 during the Late Messinian. The first two events are correlated with our PF-Events 4 and 5, whereas the last one probably predates our PF-Event 6. According to our data the co-occurrence of *G. margaritae* with dextral and sinistral forms of the *N. acostaensis* group is very typical of the Late Messinian in the Atlantic Ocean, whereas in the Early Pliocene the group is dominantly dextral. This can be observed in the Guadalquivir basin, where PF-Events 4, 5 and 6 were recorded in several sections (Sierro, 1985; Sierro et al., 1987). The coiling pattern of the *N. acostaensis* group was also analyzed by Hooper and Weaver (1987) along the Miocene/Pliocene boundary at Site 609 showing that, after a series of changes, the group became dominantly dextral during the Gilbert Chron, approximately coinciding with the Miocene/Pliocene boundary. This supports the interpretation of Benson and Rakic-El Bied (1991) assuming a Messinian age for the whole Cuevas de Almanzora section.

According to the previous discussion an attempt is made in Fig. 13 to follow the events along a traverse from the open Atlantic Ocean passing through the North Betic Gateway and Western Mediterranean and finishing in the Eastern Mediterranean.

As regards the carbon isotope record, the

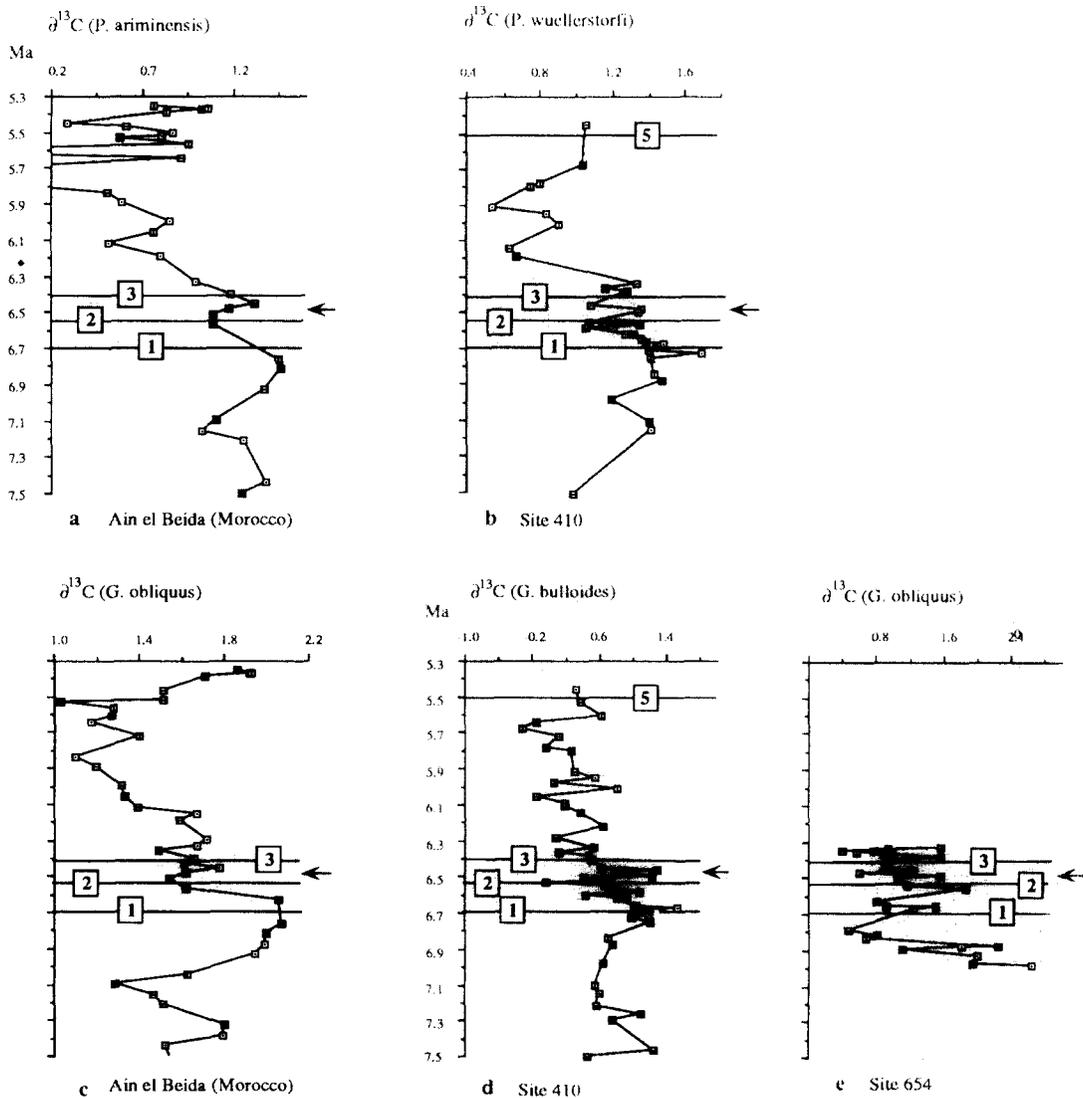


Fig. 14. Correlation between the carbon isotope curves and the main planktic foraminifera events of the Atlantic DSDP Site 410, the Ain el Beida land-based section (Morocco) and the Mediterranean ODP Site 654. Carbon isotope data after Keigwin et al. (1987), Hodell et al. (1989) and Glaçon et al. (1990), respectively. (a) and (c) Ain el Beida Section (Morocco), (b) and (d) DSDP Site 410, (e) ODP Site 654. Arrow marks the FOD of *Amaurolithus primus*.

curves of Site 410 and Morocco is evident, especially for the benthic foraminifera, as can be seen in Fig. 14. If the curves are analyzed in detail, we can recognize that the maximum $\delta^{13}\text{C}$ values both in planktic and benthic foraminifera were recorded during a short interval coinciding with PF-Event 1 (approximately from 6.9 to 6.7 Ma). From this point upwards the following trends, culminating with the

Messinian carbon shift, may be observed:

Between PF-Events 1 and 2 a first decrease in $\delta^{13}\text{C}$ of benthic and planktic foraminifera (approximately 6.7 Ma) took place prior to the FOD of *A. primus* that may be considered as a prelude to the late Miocene carbon shift.

Immediately after PF-Event 2 (top of Subchron 6r1) the $\delta^{13}\text{C}$ record tends to increase

again between PF-Events 2 and 3 (Subchron 6n1).

PF-Event 3 approximately marks the beginning of a strong decreasing trend in $\delta^{13}\text{C}$ in Morocco and in Hole 410, which was interpreted as the global Messinian carbon shift by Keigwin et al. (1987) and Hodell et al. (1989), respectively.

In the Southern Ocean, Müller et al. (1991) seem to recognize a similar carbon isotope pattern in ODP Site 704, as may be deduced by magnetostratigraphic correlation, but they do not give any information about planktic foraminifera. The beginning of the Late Miocene carbon shift in ODP Site 704 also coincides with the top of Subchron 6n1 and this event is related to a major paleoceanographic change in the Southern Ocean (Müller et al., 1991; Hodell et al., 1991; Froelich et al., 1991), characterized by important temperature and/or salinity fluctuations, variations in carbonate saturation and ventilation of deep waters. This instability in the Southern Ocean was related to the beginning of the Messinian Salinity Crisis in the Mediterranean Sea by Müller et al. (1991).

In the Tyrrhenian Sea, according to data from Glaçon et al. (1990), the carbon isotope record is very different from that globally recognized in the Open Ocean. Maximum $\delta^{13}\text{C}$ of planktic foraminifera appear in the lower core-sections (approximately 7 Ma), clearly preceding PF-Event 1 and thus diachronous with those found in the Atlantic Ocean (Fig. 14e). From 7 to 6.8 Ma an important decrease in $\delta^{13}\text{C}$ was found by Glaçon et al. (1990), which evidently is not related to the Messinian carbon shift in the global ocean.

As may be seen in Fig. 14e, the carbon isotope record in Hole 654 is anomalous, with lighter values than those found in Morocco or in Hole 410. Compared to other carbon isotope records from the Mediterranean Sea, the light $\delta^{13}\text{C}$ values in Hole 654 seem to be consistent, at least during the late Tortonian and early Messinian, previous to the Messinian

Salinity Crisis [see carbon isotope curves of Van der Zwaan (1982), Vergnaud Grazzini (1983a) and Van der Zwaan and Gudjonsson (1986) for the Falconara, Monte Giammoia and Cretan sections]. Similar, light $\delta^{13}\text{C}$ values were recorded by Van der Zwaan (1982) in benthic foraminifera of several Cretan sections during the latest Tortonian and early Messinian.

It may thus be inferred that starting in the late Tortonian, the Mediterranean surface and deep waters show a peculiar carbon isotope record different from that of the global ocean. Vergnaud Grazzini (1983b) observed that these lighter values have been characteristic of the Mediterranean deep waters since the Middle Miocene.

Considering that this difference of at least 0.8‰ in the planktic and benthic foraminifera $\delta^{13}\text{C}$ between the Atlantic Ocean and the Tyrrhenian Sea, Sicily or Crete appears to be valid for the whole Mediterranean Sea, it may be deduced that the carbon isotope record of Ain el Beida (Hodell et al., 1989) is of Atlantic affinity and, hence, deep waters in the South Rifian Gateway seem to have been of Atlantic origin.

The $\delta^{13}\text{C}$ decrease recorded by Vergnaud Grazzini (1983a) in the Lower part of the Tripoli Formation in Sicily probably represents the Mediterranean amplification of the global late Miocene carbon shift.

Globorotaliid biogeography

During the Miocene the *G. menardii* group was restricted to the tropical and subtropical region, whereas (according to our concept) the *G. miotumida* group was present in temperate areas. A very marked provincialism in the Miocene planktic foraminifera have been recognized by many authors (Jenkins, 1971, 1978; Scott, 1979, 1983; Srinivasan and Kennett, 1981; Poore, 1981; Berggren, 1984; Kennett et al., 1985; Hodell and Kennett, 1985; and others) in both hemispheres of the Pacific, Indian and Atlantic Oceans. *Globorotalia* (*Globoco-*

nella) (*Globorotalia incognita*, *G. zealandica*, *G. miozea*, *G. conoidea*, *G. conomiozea*, *G. puncticulata* and *G. inflata*) preferentially occurred in temperate water masses and was absent in tropical waters, whereas *Globorotalia* (*Menardella*) (*G. menardii*, *G. limbata*, *G. multicamerata*) and *Globorotalia* (*Globorotalia*) are distributed across the tropical and subtropical waters (Srinivasan and Kennett, 1981).

Berggren (1984) suggested the existence of sharper thermal gradients in the North Pacific Ocean than in the North Atlantic Ocean during the late Miocene (see also the biogeographic maps of Kennett et al., 1985). According to our data, planktic foraminiferal provincialism does not seem to be well defined in the North Atlantic, at least until the Messinian, since the *G. miotumida* group has rarely been recorded in the area studied prior to that period.

In the North Atlantic Ocean the *G. menardii* group extends throughout the temperate zone up to the latest Tortonian. Then a first southward retreat of the group probably took place

from a part of the North Atlantic (PF-Event 1; see Site 410, Guadalquivir basin, South Rifian basin and the Mediterranean Sea). We also believe that during the short interval in which the group is absent or sporadic, a change from sinistral to dextral took place in the *G. menardii* group. This change may probably be correlated with the one found in the N17 Zone at DSDP Sites 214 and 289 in the Tropical Indian and Pacific Oceans (Heath and McGowan, 1984) and in the eastern Atlantic (Berggren, 1984).

At the Tortonian/Messinian boundary an important change occurred in the assemblages of keeled globorotaliids of the Mediterranean Sea and N. Atlantic; this is manifested by the replacement of the *G. menardii* group by the *G. miotumida* group. This change can therefore be interpreted as a southward migration of northern temperate faunas replacing the subtropical ones along the eastern boundary current, probably due to the increasing latitudinal thermal gradients in the North Atlantic Ocean.

An increasing circulation intensity in the

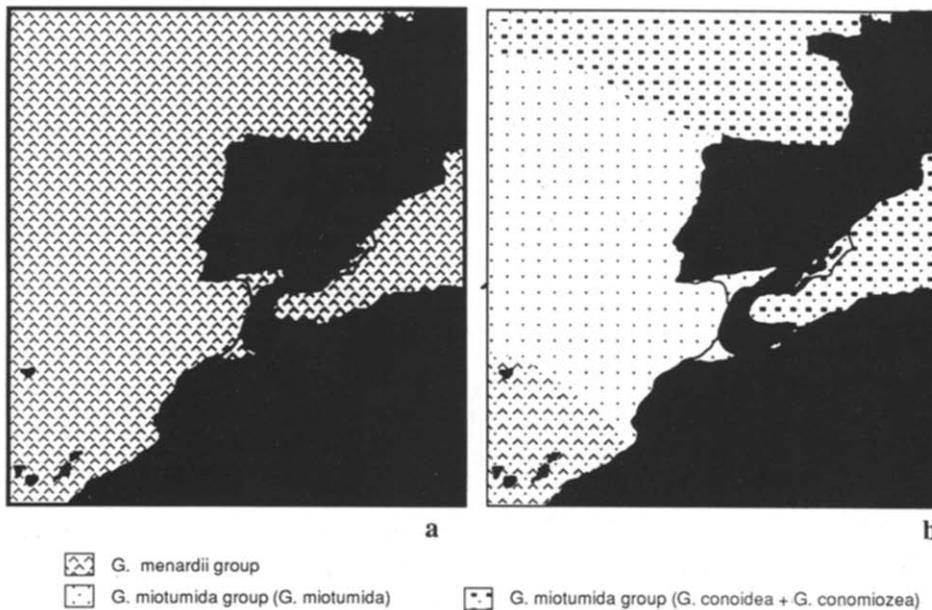


Fig. 15. Simplified paleogeographic maps showing the inferred distribution of the globorotaliids in the NE Atlantic and Mediterranean. (a) Tortonian. (b) Messinian.

North Atlantic subtropical gyre near the Tortonian/Messinian boundary was suggested by Benson et al. (1991); this would have led to a better definition of the faunal boundaries and water masses during the late Miocene. These authors recognized that in Morocco the replacement of the *G. menardii* group by *G. miotumida* group strikingly coincides with the occurrence of a psychrospheric fauna in the South Rifian Gateway. Both events led them to deduce the existence of a current reversal in the Gateway at the Tortonian/Messinian boundary that they called the "siphon event".

Populations of the *G. menardii* group were restricted during the Messinian to the tropical and subtropical zones. Specimens of this group coexisted with *G. miotumida* at Sites 397 and 416, and, sporadically, in the South Rifian basin.

According to our data and those of other authors (Bizon et al., 1972; Zachariasse, 1975; Poore and Berggren, 1975; D'Onofrio et al., 1975; Salvatorini and Cita, 1979; Cita and Vismara Schilling, 1980; Poore, 1981; Rakic-El Bied, 1990) we have observed that each taxon of the *G. miotumida* group had a particular distribution during the Messinian. In general, throughout the Mediterranean Sea *G. conomiozea* or *G. conoidea* were abundant, though occasionally or locally the *G. miotumida* morphotype was dominant (Fig. 15).

In the NE Atlantic the distribution of the different forms of the group seem to be related to latitude since *G. conomiozea* and *G. conoidea* appear preferentially at mid to high latitudes while *G. miotumida* appears at low latitudes and has been found at least as far south as to 25°N.

The most abrupt biogeographic change is found precisely at the interface between the Mediterranean and Atlantic waters, since in both the Guadalquivir basin and the South Rifian basin, there is an almost complete predominance of *G. miotumida*, whereas in the adjacent Mediterranean basins, such as Almeria, Malaga, Murcia, Alicante, Alboran,

Boudinar, etc., *G. conomiozea* is dominant (Bizon et al., 1972; Montenat, 1975; Houzay et al., 1975; Montenat et al., 1975; Carrasco et al., 1977; Gonzalez Donoso and Serrano, 1977a; Manuputti, 1977; Civis et al., 1979; and others).

The FOD of *G. conomiozea* and *G. mediterranea* in the Mediterranean Sea is hence the result of migration of the North Atlantic bioprovinces, not an in situ evolution (Zachariasse, 1975; Sierro, 1985). When the northern temperate *G. miotumida* group reached the entrance of the Betic and Rifian Gateways, it spread across the whole Mediterranean Sea. At first, the delicate low convex forms (*G. miotumida* s.s.) were dominant, but these were soon partially replaced by the higher, conical forms (*G. conomiozea*, *G. mediterranea*, *G. conoidea*, etc.).

Conclusions

A succession of events was identified in several Late Miocene DSDP Sites of the NE Atlantic, North Betic and South Rifian Gateways and Western Mediterranean based on the main changes in the assemblages of the keeled and unkeeled globorotaliids.

These events were correlated with the magnetostratigraphic scale following the paleomagnetic data of Channell et al. (1990) for ODP Site 654 (Tyrrhenian Sea) and Benson et al. (1991) for the Ain el Beida section (Morocco).

PF-Event 1, defined by the last occurrence or reduction of group I of *G. menardii* (sinistral) (subchron 7n1, 6.7 Ma) is followed by PF-Event 2 characterized by the occurrence of abundant forms of the *G. menardii* group II (dextral) (subchron 6r2, 6.56 Ma). PF-Event 3, characterized by the replacement of the *G. menardii* group II by the *G. miotumida* group (subchron 6n1, 6.4 Ma), is prominent in all the sections and is approximately correlated with the Tortonian/Messinian boundary. This change may be interpreted as a southward mi-

gration of northern Atlantic temperate faunas replacing the subtropical ones, probably caused by increasing latitudinal thermal gradients. At the same time, this event is contemporary to the first evidence of the Mediterranean crisis identified by the spreading of anoxic conditions in intermediate and deep waters during the deposition of the Tripoli Formation.

During the Late Messinian 3 events are recognized; PF-Event 4, defined by the first common occurrence of dextral forms in the populations of the *N. acostaensis* group (subchron 5r1, 5.6–5.5 Ma), occurred shortly prior to PF-Event 5 (subchron 5r1) characterized by the reduction or last occurrence of the *G. miotumida* group. Both events have been widely recognized in the Mediterranean Sea immediately below the Lower Evaporites. PF-Event 6 is defined by the first common occurrence of *G. margaritae* s.s. (subchron 5n1).

As regards the unkeeled globorotaliids, four changes in the coiling direction of the *G. scitula* group are recorded and cited as PF-Events A, B, C and D.

This succession of PF-events is also correlated with the carbon isotope curves recorded in Hole 410 by Keigwin et al. (1987) and in the Ain el Beida section (Morocco) by Hodell et al. (1989) and Benson et al. (1991). Maximum $\delta^{13}\text{C}$ values coincide with PF-Event 1 in DSDP Site 410 and Morocco, whereas a first decrease in benthic and planktic foraminiferal $\delta^{13}\text{C}$ took place between PF-Events 1 and 2, increasing again immediately after PF-Event 2. The beginning of the global Messinian carbon shift approximately coincides with PF-Event 3.

In the Tyrrhenian Sea, the strong decrease in $\delta^{13}\text{C}$ found by Glaçon et al. (1990) clearly precedes PF-Event 1 and hence is not related to the Messinian carbon shift of the global ocean as suggested by Kastens and Mascle (1990).

Acknowledgements

This work was supported by a grant from CAICYT (projects Nos. PB85-0315-CO2-00

and PB89-0398-CO2-00). Many of the samples studied were provided by the Ocean Drilling Program and Deep Sea Drilling Project, whose assistance we gratefully acknowledge. We thank W.A. Berggren and Kou-Yen Wei for their valuable suggestions and critical reviewing of the original version of this manuscript. Carlos Santisteban and Isabel Zamarreño kindly provided samples from the Fortuna basin. The detailed comments of three anonymous reviewers greatly helped to improve the original manuscript.

References

- Beckman, J.P., 1972. The Foraminifera and some associate microfossils of Sites 135 to 144. Init. Rep. DSDP, 14: 389–420.
- Bender, M.L. and Graham, D.W., 1981. On late Miocene abyssal hydrography. Mar. Micropaleontol., 6(5/6): 451–464.
- Benson, R.H. and Rakic-El Bied, K., 1991. The Messinian parastrototype at Cuevas de Almanzora, Vera basin, SE Spain: Refutation of the deep-basin, shallow water hypothesis? Micropaleontology, 37(3): 289–302.
- Benson, R.H., Rakic-El Bied, K. and Bonaduce, G., 1991. An important current reversal (influx) in the Rifian Corridor (Morocco) at the Tortonian/Messinian boundary: The End of Tethys Ocean. Paleocyanography, 6(1): 165–192.
- Berggren, W.A., 1972. Cenozoic biostratigraphic and paleobiogeography of the North Atlantic. Init. Rep. DSDP, 12: 965–1002.
- Berggren, W.A., 1984. Neogene planktonic foraminiferal biostratigraphy and biogeography: Atlantic, Mediterranean, and Indo-Pacific Regions. In: N. Ikebe and R. Tsuchi (Editors), Pacific Neogene Datum Planes. (Contributions to Biostratigraphy and Chronology.) Univ. Tokyo Press, pp. 111–161.
- Berggren, W.A., Kent, D.V. and Van Couvering, J.A., 1985. The Neogene: part II. Neogene geochronology and chronostratigraphy. In: N.J. Snelling (Editor), The Chronology of the Geological Record. Geol. Soc. London Mem., 10: 211–250.
- Bizon, G., Bizon, J.J. and Montenat, Ch., 1972. Le Miocène terminal dans le Levant espagnol (province d'Alicante et de Murcia). Rev. Inst. Fr. Pét., 27(6): 831–862.
- Borsetti, A.M., Curzi, P.V., Landuzzi, V., Mutti, M., Ricci Lucchi, F., Sartori, R., Tomadin, L. and Zuffa, G.G., 1990. Messinian and pre-Messinian sediments from ODP Leg 107 Sites 652 and 654 in the Tyrrhenian Sea: sedimentologic and petrographic study and possible

- comparisons with Italian sequences. Proc. ODP, Sci. Results, 107: 169–186.
- Bossio, A., Rakic El-Bied, K., Giannelli, L., Mazzei, R., Russo, A. and Salvatorini, G., 1976. Correlation de quelques sections stratigraphiques du Mio-Pliocène de la zone Atlantique du Maroc avec les stratotypes du Bassin Méditerranéen sur la base des Foraminifères planctoniques, Nannoplancton calcaire et Ostracodes. Atti Soc. Toscana Sci. Nat. Mem., 83: 121–137.
- Bukry, D., 1973. Low latitude coccolith biostratigraphy zonation. Init. Rep. DSDP, 15: 685–703.
- Carrasco, F., González Donoso, J.M., Linares, D., Rodríguez, P. and Serrano, F., 1977. Sobre la presencia de materiales del Mioceno superior en la desembocadura del río Velez (provincia de Málaga). Seminario sobre el Messiniense. (Málaga, 1977.) 3: 17–19.
- Cepek, P. and Gartner, S., 1980. Cenozoic calcareous nannoplankton fossils, Deep Sea Drilling Project Site 415 and 416, Moroccan basin. Init. Rep. DSDP, 50: 333–345.
- Cifelli, R., 1976. Evolution of Ocean climate and the record of planktonic foraminifera. Nature, 264(5585): 431–432.
- Cifelli, R. and Glaçon, G., 1979. New late Miocene and Pliocene occurrences of *Globorotalia* species from the north Atlantic; and a paleogeographic review. J. Foraminiferal Res., 9 (3): 210–227.
- Cita, M.B. and Ryan, W.B.F., 1978. The Bou Regreg section of the Atlantic Coast of Morocco, evidence timing and significance of a late Miocene regressive phase. Riv. Ital. Paleontol. Stratigr., 84(4): 1051–1058.
- Cita, M.B. and Vismara Schilling, A., 1980. Planktonic foraminiferal assemblages across the Miocene/Pliocene boundary at Deep Sea Drilling Project Sites 415 and 416, and correlations with other north Atlantic successions. Init. Rep. DSDP, 50: 497–506.
- Civis, J., Porta, J. and Martinell, J., 1979. Microfauna del Mioceno terminal de la Rambla de Arejos (Almería). Stud. Geol., 15: 37–55.
- Colalongo, M.L., Di Grande, A., D'Onofrio, S., Giannelli, L., Iaccarino, S., Mazzei, R., Romeo, M. and Salvatorini, G., 1979. Stratigraphy of Late Miocene Italian sections straddling the Tortonian/Messinian boundary. Boll. Soc. Paleontol. Ital., 18(2): 258–302.
- Channell, J.E.T., Torii, M. and Hawthorne, T., 1990. Magnetostratigraphy of sediments recovered during Leg 107. Proc. ODP, Sci. Results, 107: 335–346.
- D'Onofrio, S., Giannelli, L., Iaccarino, S., Morlotti, E., Romeo, M., Salvatorini, G., Sampo, M. and Sprovieri, R., 1975. Planktonic foraminifera of the Upper Miocene from some Italian sections and the problem of the lower boundary of the Messinian. Boll. Soc. Paleontol. Ital., 14(2): 177–196.
- Feinberg, H. and Lorenz, H.G., 1970. Nouvelles données stratigraphiques sur le Miocène supérieur et le Pliocène de Maroc-occidental. Notes Serv. Geol. Maroc, 30(225): 21–26.
- Flores, J.A., 1985. Nanoplancton calcáreo en el Neógeno del borde Noroccidental de la cuenca del Guadalquivir (SO de España). Doct. Thesis, Univ. Salamanca, 715 pp. (Unpubl.).
- Flores, J.A. and Sierro, F.J., 1987. Calcareous plankton in the Tortonian/Messinian transition series of the Northwestern edge of the Guadalquivir basin. Abh. Geol. Bundesanst., 39: 67–84.
- Flores, J.A. and Sierro, F.J., 1989. Calcareous nannoflora and planktonic foraminifera in the Tortonian/Messinian boundary interval of East Atlantic DSDP Sites and their relation to Spanish and Moroccan sections. In: S.E. van Heck and J. Crux (Editors), Nannofossils and Their Applications. Br. Micropalaeontol. Soc. Ser., pp. 249–266.
- Flores, J.A., Sierro, F.J. and Glaçon, G., in press. Calcareous plankton analysis in the preevaporitic sediments of the ODP Site 654 (Tyrrhenian Sea, Western Mediterranean). Micropaleontology.
- Froelich, P.N., Malone, P.N., Hodell, D.A., Ciesielski, P.F., Warnke, D.A., Westall, F., Hailwood, E.A., Nobes, D.C., Fenner, J., Mienert, J., Mwenifumbo, C.J. and Müller, D.W., 1991. Biogenic opal and carbonate accumulation rates in the subantarctic South Atlantic: The Late Neogene of Meteor Rise Site 704. Proc. ODP, Sci. Results, 114: 515–532.
- Glaçon G., Vergnaud Grazzini, C., Iaccarino, S., Rehault, J.P., Randrianasolo, A., Sierro, F.J., Weaver, P., Channell, J., Torii, M. and Hawthorne, T., 1990. Planktonic foraminiferal events and stable isotope record in the Upper Miocene of the Tyrrhenian Sea, ODP Site 654, leg 107. Proc. ODP, Sci. Results, 107: 415–427.
- González Donoso, J.M. and Serrano, F., 1977a. Bio y Cronoestratigrafía de los materiales pre-evaporíticos de Sorbas (provincia de Almería). Seminario sobre el Messiniense, Málaga, 3 Excursión No. 2: 69–76.
- González Donoso, J.M. and Serrano, F., 1977b. Precisiones sobre la bioestratigrafía del corte de Cuevas de Almanzora. Cuad. Geol. Univ. Granada, 8: 241–252.
- Hamilton, N., 1979. A paleomagnetic study of sediments from Site 397 Northwest African Continental margin. Init. Rep. DSDP, 47(1): 463–477.
- Haq, B.U., Worsley, T.R., Burckle, L.H., Douglas, R.G., Keigwin, L.D., Opdyke, N.D., Savin, S.H., Sommer, M.A., Vincent, E. and Woodruff, F., 1980. Late Miocene carbon-isotopic shift and synchronicity of some phytoplanktonic biostratigraphic events. Geology, 8: 427–431.
- Heath, R.H. and McGowran, B., 1984. Neogene datum planes: foraminiferal successions in Australia with reference sections from the Ninetyeast Ridge and the Ontong–Java Plateau. In: N. Ikebe and R. Tsuchi (Editors), Pacific Neogene Datum Planes. (Contributions to Biostratigraphy and Chronology.) Univ. Tokyo Press, pp. 187–191.
- Hodell, D.A. and Kennett, J.P., 1985. Miocene paleo

- ceanography of the South Atlantic Ocean at 22, 16, and 8 Ma. In: J.P. Kennett (Editor), *The Miocene Ocean: Paleoceanography and Biogeography*. Geol. Soc. Am. Mem., 163: 317–337.
- Hodell, D.A. and Kennett, J.P., 1986. Late Miocene–early Pliocene stratigraphy and paleoceanography of the south Atlantic and southwest Pacific Oceans: a synthesis. *Paleoceanography*, 1(3): 285–311.
- Hodell, D.A., Benson, R.H., Kennett, J.P. and Rakic-El Bied, K., 1989. Stable isotope stratigraphy of late Miocene–early Pliocene sequences in Northwest Morocco: the Bou Regreg Section. *Paleoceanography*, 4(4): 467–482.
- Hodell, D.A., Müller, D.W., Ciesielski, P.F. and Mead, G., 1991. Synthesis of oxygen and carbon isotopic results from Site 704: implications for major climatic–geochemical transitions during the Late Neogene. *Proc. ODP, Sci. Results*, 114: 475–480.
- Hooper, P.W.P. and Weaver, P.P.E., 1987. Paleoceanographic significance of Late Miocene to Early Pliocene planktonic foraminifers at Deep Sea Drilling Project Site 609. *Init. Rep. DSDP*, 94(2): 925–934.
- Houzay, J.P., Hilali, E.A., Faure-Muret, A., Glaçon, G., Choubert, G. and Nesteroff, W.D., 1975. La stratigraphie du Néogène du bassin de Boudinar, Rif oriental, et le problème du Messinien. *C. R. Acad. Sci. Paris*, 280D: 2729–2732.
- Hsü, K.J., 1985. Unresolved problem concerning the Messinian salinity crisis. *G. Geol.*, 47(1/2): 203–212.
- Iaccarino, S. and Salvatorini, G., 1979. Planktonic foraminiferal biostratigraphy of the Neogene and Quaternary sediments from Site 398, DSDP Leg 47B. *Init. Rep. DSDP*, 47(2): 237–254.
- Jenkins, D.G., 1971. New Zealand Cenozoic Planktonic Foraminifera. *N.Z. Geol. Surv. Paleontol. Bull.*, 42, 278 pp.
- Jenkins, D.G., 1978. Neogene planktonic foraminifers from DSDP Leg 40, Sites 360 and 362 in the South-eastern Atlantic. *Init. Rep. DSDP*, 40: 723–739.
- Kastens, K. and Mascle, J., 1990. Did a glacio-eustatic-level drop trigger the Messinian salinity crisis in the Mediterranean? *Proc. ODP, Sci. Results*, 113: 993.
- Keigwin, L.D., 1979. Late Cenozoic stable isotope stratigraphy and paleoceanography of DSDP Sites from the east equatorial and north central Pacific Ocean. *Earth Planet. Sci. Lett.*, 45: 361–382.
- Keigwin, L.D. and Shackleton, N.J., 1980. Uppermost Miocene carbon isotope stratigraphy of a piston core in the equatorial Pacific. *Nature*, 284: 613–614.
- Keigwin, L.D., Aubry, M.P. and Kent, D.V., 1987. North Atlantic late Miocene stable-isotope stratigraphy, biostratigraphy, and magnetostratigraphy. *Init. Rep. DSDP*, 94(2): 935–963.
- Kennett, J.P., Keller, G. and Srinivasan, M.S., 1985. Miocene planktonic foraminiferal biogeography and paleoceanographic development of the Indo-Pacific region. In: J.P. Kennett (Editor), *The Miocene Ocean: Paleoceanography and Biogeography*. Geol. Soc. Am. Mem., 163: 197–236.
- Krasheninnikov, V.A., 1979. Stratigraphy and planktonic foraminifers of Cenozoic deposits of the bay of Biscay and Rockall Plateau, DSDP Leg 48. *Init. Rep. DSDP*, 48: 431–450.
- Langereis, C.G., Zachariasse, W.J. and Zijdeveld, J.D.A., 1984. Late Miocene magnetobiostratigraphy of Crete. *Mar. Micropaleontol.*, 8(4): 261–281.
- Lukowski, P., Wernli, R. and Poisson, A., 1988. Mise en évidence de l'importance des dépôts messiniens dans le bassin Miocene de Fortuna (Prov. de Murcia), Espagne. *C. R. Acad. Sci. Paris*, 307: 941–947.
- Manuputti, J.A., 1977. Notes on the late Miocene planktonic foraminiferal associations of the Lorca basin (province of Murcia, SE Spain). *Seminario sobre el Messiniense*. (Málaga, 1977.) 3: 71–76.
- Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: A. Farinacci (Editor), *Proc. 2nd Planktonic Conf.* (Roma.) Edizioni Tecnoscienza, Rome, pp. 739–786.
- Mazzei, R., Raffi, I., Rio, D., Hamilton, N. and Cita, M.B., 1979. Calibration of the late Neogene calcareous plankton datum planes with the paleomagnetic record of Site 397 and correlation with Moroccan and Mediterranean sections. *Init. Rep. DSDP*, 47(1): 375–389.
- Montenat, Ch., 1975. Le Miocene terminal des Chaines Betiques (Espagne meridionale). *Esquisse paleogeographique*. In: C.W. Drooger (Editor), *Messinian Events in the Mediterranean*. Kon. Ned. Akad. Wet., North-Holland, Amsterdam, pp. 180–187.
- Montenat, Ch., Bizon, G. and Bizon, J.J., 1975. Remarques sur le forage Joides 121 en mer d'Alboran (Méditerranée occidentale). *Bull. Geol. Soc. Fr.*, (7), 17(1): 45–51.
- Montenat, C., Bizon, G., Bizon, J.J., Carbonnel, G., Müller, C. and Reneville, J., 1976. Continuité ou discontinuité de sédimentation marine Mio-Pliocene en Méditerranée Occidentale, l'exemple de Vera (Espagne meridionale). *Rev. Inst. Fr. Pét.*, 31(4): 613–663.
- Moreau, M.G., Feinberg, H. and Pozzi, J.P., 1985. Magnetostratigraphy of a Late Miocene section from the Moroccan Atlantic margin. *Earth Planet. Sci. Lett.*, 76(1/2): 167–175.
- Müller, D.W. and Hsü, K.J., 1987. Event stratigraphy and paleoceanography in the Fortuna basin (Southeast Spain): a Scenario for the Messinian salinity crisis. *Paleoceanography*, 2(6): 679–696.
- Müller, D.W., Hodell, D.A. and Ciesielski, P.F., 1991. Late Miocene to Earliest Pliocene (9.8–4.5 Ma) paleoceanography of the subantarctic southeast Atlantic: stable isotopic, sedimentologic and microfossil evidence. *Proc. ODP, Sci. Results*, 114: 459–474.
- Poore, R.Z., 1978. Oligocene through Quaternary plank-

- tonic foraminiferal biostratigraphy of the North Atlantic: DSDP Leg 49. Init. Rep. DSDP, 49: 447–517.
- Poore, R.Z., 1981. Late Miocene biogeography and paleoclimatology of the central north Atlantic. *Mar. Micropaleontol.*, 6(5/6): 599–616.
- Poore, R.Z. and Berggren, W.A., 1975. Late Cenozoic planktonic foraminiferal biostratigraphy and paleoclimatology of Hatton–Rockall basin: DSDP Site 116. *J. Foraminiferal Res.*, 5(4): 270–293.
- Rakic-El Bied, K., 1990. Stratigraphie à haute resolution et paleo-océanographie au Maroc à la fin du Miocene: apport des Foraminifères planctoniques. Thesis, Univ. Bordeaux I.
- Santisteban, C. and Taberner, C., 1983. Shallow marine and continental conglomerates derived from coral reef complexes after dessication of a deep marine basin: the Tortonian–Messinian deposits of the Fortuna basin, SE Spain. *J. Geol. Soc. London*, 140: 401–411.
- Salvatorini, G. and Cita, M.B., 1979. Miocene foraminiferal stratigraphy, DSDP Site 397 (Cape Bojador, North Atlantic). Init. Rep. DSDP, 47(1): 317–375.
- Savin, S.M., Douglas, R.G., Keller, G., Killingley, Shaughnessy, L., Sommer, M.A., Vincent, E. and Woodruff, F., 1981. Miocene benthic foraminiferal isotope records: a synthesis. *Mar. Micropaleontol.*, 6(5/6): 423–450.
- Scott, G.H., 1979. The late Miocene to early Pliocene history of the *Globorotalia miozea* plexus from Blind River, New Zealand. *Mar. Micropaleontol.*, 4(4): 341–361.
- Scott, G.H., 1983. Biostratigraphy and histories of Upper Miocene–Pliocene *Globorotalia* south Atlantic and southwest Pacific. *Mar. Micropaleontol.*, 7(5): 369–383.
- Sierro, F.J., 1984. Foraminíferos planctónicos y bioestratigrafía del Mioceno superior–Plioceno del borde occidental de la cuenca del Guadalquivir (SO de España). Doct. Thesis, Univ. Salamanca, 391 pp. (Unpubl.).
- Sierro, F.J., 1985. The replacement of the “*Globorotalia menardii*” group by the *Globorotalia miotumida* group: an aid to recognizing the Tortonian/Messinian boundary in the Mediterranean and adjacent Atlantic. *Mar. Micropaleontol.*, 9(6): 525–535.
- Sierro, F.J., Flores, J.A., Civis, J. and Gonzalez Delgado, J.A., 1987. New criteria for the correlation of the Andalusian and Messinian stages. *Ann. Inst. Geol. Publ. Hung.*, LXX: 355–361.
- Srinivasan, N.S. and Kennett, J.P., 1981. Neogene planktonic foraminiferal biostratigraphy and evolution: equatorial to subantarctic, South Pacific. *Mar. Micropaleontol.*, 6: 499–533.
- Stainforth, R.M., Lamb, J.L., Luterbacher, H., Beard, J.H. and Jeffords, R.M., 1975. Cenozoic Planktonic zonation and characteristics of Index forms. *Univ. Kans. Paleontol. Contrib.*, 62, 425 pp.
- Tjalsma, R.C., 1971. Stratigraphy and Foraminifera of the Neogene of the Eastern Guadalquivir Basin, S. Spain. *Utrecht Micropaleontol. Bull.*, 4, 161 pp.
- Van der Zwaan, G.J., 1982. Paleoecology of Late Miocene Mediterranean Foraminifera. *Utrecht Micropaleontol. Bull.*, 25, 202 pp.
- Van der Zwaan, G.J. and Gudjonsson, L., 1986. Middle Miocene–Pliocene stable isotope stratigraphy and paleoceanography of the Mediterranean. *Mar. Micropaleontol.*, 10(1/3): 71–90.
- Vergnaud Grazzini, C., 1983a. Major Cenozoic climatic changes: the stable isotope record of marine carbonates in the world Ocean—a review. *Paleobiologie Continentale*, XIV(2): 433–473.
- Vergnaud Grazzini, C., 1983b. Reconstruction of Mediterranean Late Cenozoic hydrography by means of carbon isotope analyses. In: J.E. Meulenkamp (Editor), *Reconstruction of Marine Paleoenvironments*. *Utrecht Micropaleontol. Bull.*, 30: 25–47.
- Vincent, E.K., Killingley, J.S. and Berger, W.H., 1985. Miocene oxygen and carbon isotope stratigraphy of the tropical Indian Ocean. In: J.P. Kennett (Editor), *The Miocene Ocean: Paleoceanography and Biogeography*. *Geol. Soc. Am. Mem.*, 163: 103–130.
- Wernli, R., 1977. Les Foraminifères planctoniques de la limite Mio-Pliocène des environs de Rabat (Maroc). *Eclogae Geol. Helv.*, 70(1): 143–191.
- Woodruff, F. and Savin, S.M., 1985. $\delta^{13}\text{C}$ values of Miocene Pacific benthic foraminifera: Correlations with the sea level and biological productivity. *Geology*, 13: 119–122.
- Zachariasse, W.J., 1975. Planktonic Foraminiferal Biozonation of the Late Neogene of Crete (Greece). *Utrecht Micropaleontol. Bull.*, 11, 171 pp.
- Zachariasse, W.J., 1979. Planktonic foraminifera from section Potamida 1: taxonomic and phyletic aspects of keeled globorotaliids and some paleoenvironmental estimates. In: C.W. Drooger, J.E. Meulenkamp, C.G. Langereis et al. (Editors), *Problems of Detailed Biostratigraphic and Magnetostratigraphic Correlations in the Potamidha and Apostoli Sections of the Cretan Miocene*. *Utrecht Micropaleontol. Bull.*, 21: 129–166.