Early Late Pliocene Biochronology and Surface Water Temperature Variations in the Mediterranean

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Abstract

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A high-resolution magnetobiostratigraphy is presented for the early Late Pliocene in Sicily. Paleomagnetic measurements on samples from 100 stratigraphic levels provide an unprecedented high-quality polarity sequence which extends from the upper reversed Gilbert to the upper normal Gauss subchron. The resultant chronology for the early Late Pliocene provides ages for the following principal Mediterranean bioevents: (1) FOD *Globorotalia crassaformis* at 3.40 Ma, (2) prolonged absence of *Globorotalia puncticulata* between 3.38 and 3.16 Ma, (3) LOD *Uvigerina rutula* at 3.16 Ma, (4) LOD *Sphaeroidinellopsis seminulina* at 3.07 Ma, (5) LOD *Globoquadrina altispira* at 3.04 Ma and (6) LOD *Cibicides italicus* at 2.96 Ma.

Summer and winter surface water temperature estimates for the period 3.50 to 2.92 Ma are based on the abundances of *Globigerinoides sacculifer* and *Globorotalia puncticulata* in 111 samples with an average resolution of some 5000 years.

Short-term variations in temperature of the surface water and in colour and carbonate content of the sediment are primarily controlled by the equinoxial precession. A higher seasonality during deposition of the grey-coloured, carbonate-poor facies suggests that at that time the summer solstice occurred near perihelion, whereas an inverse alignment occurred at the time of deposition of white-coloured, carbonate-rich layers. This phase-relationship between the precession cycle and grey-coloured layers is also valid for the sapropels which began to intercalate in the grey-coloured layers at 2.94 Ma.

Long-term changes in surface water temperatures include a warming between 3.38 and 3.18 Ma followed by a cooling from 3.18 to 3.03 Ma. The warming of Mediterranean surface waters at 3.38 Ma is believed to be associated with the final closure of the Isthmus of Panama. Consequent strengthening of the Gulf Stream injected larger volumes of warm surface water into the North Atlantic Drift and eastern boundary current and this caused surface water temperatures in the mid to high-latitude northeast Atlantic and Mediterranean to rise. The subsequent climatic cooling at 3.18 Ma is linked to a first stage of Northern Hemisphere continental ice growth.

Introduction

Despite the long tradition in Pliocene stratigraphy in the Mediterranean there is still surprisingly little paleomagnetic control. Good paleomagnetic records are presently available for the Early Pliocene (Zijderveld et al., 1986; Hil-

gen and Langereis, 1988) and the Late Pliocene to earliest Pleistocene (Tauxe et al., 1983) and provide accurate age-estimates for the Miocene/Pliocene and Pliocene/Pleistocene boundaries. The Miocene/Pliocene boundary is anchored slightly below the base of the Thvera subchron with an age of 4.86 Ma (Hilgen and

Langereis, 1988), whereas the Pliocene/Pleistocene boundary lies slightly above the Olduvai subchron at approximately 1.6 Ma (Tauxe et al., 1983). Good paleomagnetic control on the early Late Pliocene, however, is still lacking and current biochronologies for this time-span are based on transferring ages of extra-Mediterranean bioevents to Mediterranean equivalents (Rio et al., 1984) or on the employment of periodicities of sedimentary cycles (Hilgen, 1987).

The early Late Pliocene is the time when the climate system passed an important threshold (e.g. Shackleton and Opdyke, 1977; Keigwin, 1982a, 1987; Suc, 1984; Ruddiman et al., 1987a) but many more well-dated paleoenvironmental records are necessary to unravel the details of this climatic change.

In this paper we introduce a high-resolution magnetostratigraphy for the early Late Pliocene in Sicily, which furnishes a new and detailed biochronology for this time-span in the Mediterranean. Furthermore, the abundance record of three planktonic foraminiferal species affords a well-dated record of early Late Pliocene surface water temperature variations in the Mediterranean.

Stratigraphic data

The results presented here are based on a combined paleomagnetic and micropaleontological sampling campaign on the early Late Pliocene composite section of Punta Grande and Punta Piccola in Sicily (Fig. 1). The marly lithology of this section (Fig. 2) is strongly defined by astronomically controlled variations in carbonate content (Hilgen, 1987). Grey to white colour variations characterize small-scale cycles in which the grey interbeds are relatively poor in carbonate. Larger scale cycles are distinguishable by the occasional occurrence of prominently indurated carbonate-rich intervals. Sapropelitic interbeds in the higher part of the section correspond to the grey coloured part of the small-scale cycles. The distinct rhythmic layering of the sediment is extremely

helpful in accurately tracing faults which otherwise might upset the stratigraphic continuity.

The stratigraphic position of planktonic foraminiferal bioevents (Fig. 2) is based on a qualitative analysis of fractions coarser than 125 µm from 145 samples. In terms of the biostratigraphy of Spaak (1983) the composite section ranges from the *Globorotalia puncticulata* Zone (interval 4) into the *Globorotalia crassaformis* Zone (interval 6). In applying the MPL-zonal scheme of Cita (1975) the section extends from MPL 4 into MPL 5 (Fig. 2).

Magnetostratigraphy

Paleomagnetic samples were taken at 77 levels in the Punta Piccola section and at 20 levels in the Punta Grande section with an average sampling interval of 50 cm (Fig. 2). At each level we drilled two cores of 25 mm diameter. Special care was taken to remove the weathered surface and to drill in freshly coloured (blue) sediments. Inter-level distances were calculated according to Langereis and Meulenkaamp (1979).

The natural remanent magnetization (NRM) was measured on a 2G Enterprises cryogenic magnetometer. Total NRM intensities of the Punta Grande section, especially in the upper part, are rather low, between 0.02 and 0.20 mA/m, but well above the sensitivity of the magnetometer (0.002 mA/m). Total NRM intensities of the Punta Piccola section are high, most of them between 1.0 and 20.0 mA/m. Total NRM directions show consistent groups of normal and reversed polarity, even before demagnetization procedures have removed any viscous or secondary component.

To determine both the characteristic remanent magnetization (ChRM) and the properties of the carrier of this remanence from its decay curve (Zijderveld, 1975), generally two specimens per sampling level were demagnetized progressively by using stepwise thermal

Fig 1 Location map of the Punta Grande and Punta Piccola sections.

demagnetization with small temperature increments.

Despite their low initial intensities, specimens from the Punta Grande section produce good results with clearly reversed polarity directions (Fig. 3a,b), even though in the upper part of the section some scatter is observed (Fig. 3b). The specimens from the Punta Piccola section show almost invariably results of very good quality (Fig. 3c,d). Soft secondary components are generally small or absent. The ChRM components show very uniform directions regardless of their polarity. The demagnetization diagrams show that the maximum unblocking temperature is close to 580°C , which indicates that the characteristic component most probably resides in magnetite. The presence of magnetite suggests that the ChRM is of a primary origin.

The demagnetization diagrams furthermore show that normal and reversed directions are anti-parallel. Inclinations of the ChRM (40°) are consistently shallower than the inclinations of the geocentric axial dipole field for the locality (57.5°) or present day field (52°). This might point to an inclination error due to sediment compaction and may be taken as another

indication for the primary origin of the ChRM (Laj et al., 1982). ChRM directions obtained from progressive demagnetization are plotted in Fig. 4. Normal and reversed polarity levels are consistently grouped in distinct polarity zones. The Punta Grande section contains only reversed directions, whereas the Punta Piccola section yields three reversed and three normal polarity zones.

The next step is to correlate the composite Punta Grande and Punta Piccola polarity sequence to the magnetic polarity time scale based on sea floor anomalies (Berggren et al., 1985). In an earlier magnetobiostratigraphic study on the Early Pliocene of southern Italy, Zijdeveld et al. (1986) have shown that the *Globorotalia margaritae*–*Globorotalia puncticulata* Zone (= MPL3 of Cita, 1975 and Interval 3 of Spaak, 1983) extends up into the upper reversed Gilbert Chron. The three normal polarity zones in the composite Punta Grande and Punta Piccola section, therefore, are younger than the normal Cochita subchron and can only be correlated with the major part of the Gauss Chron (Fig. 5).

Calculated correlation coefficients between the stratigraphic thickness of the 4 Sicilian po-

Fig 2 Lithology, sample position, distribution of selected planktonic foraminifers, bioevents and biostratigraphy of the composite Punta Grande and Punta Piccola section

Fig 3 Representative thermal demagnetization vector diagrams of some selected samples in the Punta Grande section (a, b) and the Punta Piccola section (c, d). Solid (open) circles denote projection on the horizontal (vertical) plane; numbers indicate temperatures in °C.

larity zones and the time-lengths of every possible sequence of 4 polarity zones from the magnetic polarity time scale (a method introduced by Langereis et al., 1984) also indicate that the composite Punta Grande and Punta Piccola section is equivalent to the major part of the Gauss Chron.

Ages of early Late Pliocene bioevents

Small-scale sedimentary cycles (Figs. 2, 5) between the base of the Gauss Chron and the

top of the Kaena subchron have an average periodicity of 19.2 kyr which is close to the figure of 20.5 kyr for similar cycles in the Lower Pliocene of Calabria (Zijderveld et al., 1986) and of 19.1 kyr in the Lower Pliocene of Sicily (Hilgen and Langereis, 1988) and suggests that also these early Late Pliocene small-scale cycles are related to the equinoxial precession.

The upper reversed part of the Gilbert Chron contains 12 such cycles, which on the basis of a 19.2 kyr periodicity, provides an age of 3.63 Ma for the base of the section. The upper normal

Fig 4 Declination and inclination of ChRM in the Punta Grande and Punta Piccola section. Black (white) intervals represent normal (reversed) polarities. Dashed lines indicate declination of the geocentric axial dipole field for the present latitude of the locality or zero inclination

Fig. 5. Polarity sequence of the composite Punta Grande and Punta Piccola section and calibration to the magnetic polarity time scale

part of the Gauss Chron contains 11 cycles thus providing an age of 2.70 Ma for the top of the section. In the uppermost 5 cycles, sedimentation rates increase progressively upward from 5.4 to 12.5 cm/kyr. Ages of bioevents between the base of the Gauss Chron and the top of the Kaena subchron are based on linear interpolation between paleomagnetic datum levels using the polarity time scale of Berggren et al. (1985). Ages of bioevents in the upper reversed part of the Gilbert and upper normal part of the Gauss Chron are based on the number of cycles between bioevents and their nearest paleomagnetic datum level. The complete age-calibrated sequence of Mediterranean bioevents between 3.63 and 2.70 Ma is shown in Fig. 6.

The LOD of *Sphaeroidinellopsis seminulina* in the Mediterranean has earlier been correlated to the Kaena subchron (Cita and Ryan, 1973), but appears by now to be firmly anchored in the middle normal subchron of the Gauss Chron at an age of 3.07 Ma (Fig. 6). This age fits remarkably well within the reported age range of 3.08 to 2.98 Ma for this datum level in magnetobiostratigraphic records from the open ocean (Hays et al., 1969; Saito et al., 1975; Mazzei et al., 1979; Keigwin, 1982b; Weaver and Clement, 1987). Such a globally narrow time-range for the LOD of *Sphaeroidinellopsis seminulina* makes this datum level an ideal biochronohorizon in the early Late Pliocene of tropical-subtropical oceans. In contrast to the incipiently corticated *Sphaeroidinellopsis seminulina*, fully corticate representatives of *Sphaeroidinellopsis*, viz. *S. subdehiscens*, disappear much earlier, at 3.58 Ma, from the Mediterranean record (Fig. 6).

The LOD of *Globoquadrina altispira* appears to correlate with a level within the middle normal subchron of the Gauss Chron at an age of 3.04 Ma (Fig. 6). Also this age estimate compares well with the age-range of 3.10 to 2.85 Ma for the LOD of *Globoquadrina altispira* in the open ocean (Hays et al., 1969; Saito et al., 1975; Mazzei et al., 1979; Orr and Jenkins, 1980; Keigwin, 1982b; Weaver and Clement, 1987).

Although this datum level is potentially a useful biochronohorizon in the tropical-subtropical ocean, its employment in cool-subtropical regions requires high-resolution sample series because in these regions *Globoquadrina altispira* is sparse and its record discontinuous. In the early Late Pliocene of the Mediterranean (for example) *Globoquadrina altispira* is present only during 4 periods of less than 20,000 years each.

In contrast to the global time-significance of the LOD of *Sphaeroidinellopsis seminulina* and *Globoquadrina altispira* other early Late Pliocene foraminiferal events in the Mediterranean seem to be time-bound on a more regional scale. Intra-Mediterranean time-stratigraphic value probably holds for the LOD of *Uvigerina rutila* at 3.16 Ma and for the LOD of *Cibicides italicus* at 2.96 Ma. Earlier age estimates of 3.00 and 2.40 Ma for both events (Sprovieri, 1986), based on sediment accumulation curves of Mediterranean sections by employing age-calibrated extra-Mediterranean bioevents, are too young. It is remarkable that the LOD of *Cibicides italicus* coincides with an earliest diversification in deep water miliolids (Fig. 6).

Also an age of 3.40 Ma for the FOD of *Globorotalia crassaformis* is only significant for the Mediterranean region. In the central North Atlantic this species first occurs in the Nunivak subchron at 4.16 Ma together with *Globorotalia puncticulata* (Weaver and Clement, 1987). In the Mediterranean, *Globorotalia puncticulata* also arrives in the Nunivak subchron at 4.13 Ma (Zijderveld et al., 1986), but without *Globorotalia crassaformis*, which enters the Mediterranean not before 3.40 Ma. Off northwestern Africa, at DSDP site 397, *Globorotalia puncticulata* and *Globorotalia crassaformis* again arrive simultaneously (Spaak, 1983), although we think that an age-range of 4.16 to 4.13 Ma for this event is a better estimate than the poorly constrained age of 4.32 Ma (Mazzei et al., 1979). All these data indicate that the spreading of *Globorotalia crassaformis* in the Mediterranean lags behind its spreading in the adjacent Atlan-

Fig. 6. Age-calibrated abundances of *Globigerinoides sacculifer*, *Globorotalia puncticulata* and *Globigerina falconensis* and bioevents for the early Late Pliocene of Sicily. *Globigerinoides sacculifer* reflects summer (SSTs) and *Globorotalia puncticulata* winter surface water temperatures (SSTw). Major changes in Mediterranean surface water temperatures are summarized and linked to major events in circulation and climate in the North Atlantic.

tic by at least 730,000 years. The early Late Pliocene record of *Globorotalia crassaformis* in the Mediterranean shows three intervals of dominantly right-coiled populations and two longer-term intervals in which this species is virtually absent (Fig. 6). This age-calibrated pattern provides a useful addition to the early Late Pliocene biochronology of the Mediterranean.

The early Late Pliocene record of *Globorotalia puncticulata* shows that this species is absent in the Mediterranean from 3.38 to 3.16 Ma (Fig. 6) which is remarkably consistent with the record of the central North Atlantic DSDP site 609 (Raymo et al., 1987). At 3.16 Ma Med-

iterranean populations of *Globorotalia puncticulata* start to slightly diverge morphologically from their Atlantic equivalents and on that basis Mediterranean populations are generally singled out as a separate species, viz. *Globorotalia bononiensis*. In reality, however, *Globorotalia bononiensis* is only an ecophenotype of *Globorotalia puncticulata* whose LOD in the Mediterranean has an estimated age of 2.31 Ma (Hilgen, 1987) and, therefore, is time-equivalent with the LOD of *Globorotalia puncticulata* in the central North Atlantic (Weaver and Clement, 1987). Since we wish to avoid self-made age discrepancies between the records of

Globorotalia puncticulata in the Mediterranean and in the open ocean, *Globorotalia bononiensis* is included in *Globorotalia puncticulata*.

Surface water temperature index

A quantitative analysis on the early Late Pliocene planktonic foraminiferal fauna of Sicily includes the counting of 16 categories at 111 levels between 3.50 and 2.92 Ma. In this paper we focus on the abundance distribution of only three species, viz. *Globorotalia puncticulata*, *Globigerinoides sacculifer* and *Globigerina falconensis*.

Amongst these three species *Globorotalia puncticulata* is extinct. Its living relative *Globorotalia inflata* is often classified as a transitional species (e.g. Tolderlund and Bé, 1971) but such a qualification is rather meaningless as long as habitat characteristics are not specified. According to Van Leeuwen (1988) *Globorotalia inflata* flourishes in thermally homogeneous and cool surface waters with intermediate food levels. These habitat characteristics agree perfectly with high winter abundances of this species in the mid-latitude northwest Atlantic (Tolderlund and Bé, 1971; Hemleben and Spindler, 1983). Winter blooming of *Globorotalia inflata* in this region coincides with cooling and stirring of the surface water which erodes the summer thermocline, deepens the mixed layer and supplies the photic layer with nutrients. Also along the Iberian coast and in the western Mediterranean *Globorotalia inflata* attains highest abundances during winter (cf. winter plankton haul data of Glacon et al., 1974 and Duprat, 1983, with summer data of Bé and Hamlin, 1967 and Cifelli, 1974), when the upper layer is almost homothermal down to 200 m (McGill, 1961) and surface water temperatures fall below 16°C (Duprat, 1983).

Summarizing, modern winter faunas in the mid-latitude North Atlantic and western Mediterranean are characterized by high abundances of *Globorotalia inflata* when the photic layer is cool, homothermal and relatively pro-

ductive. We assume that the precursor of *Globorotalia inflata*, viz. *Globorotalia puncticulata*, had similar habitat characteristics.

Globigerinoides sacculifer is an extant species which presently abounds in warm-subtropical to tropical waters (e.g. Bé and Hutson, 1977). This species is stenothermic with high minimum surface water temperature requirements (e.g. Bé and Hutson, 1977). This is nicely illustrated by the virtual absence of *Globigerinoides sacculifer* in the Gulf of Aqaba in glacial times when minimum surface water temperatures dropped below 18°C (Luz and Reiss, 1983). In the mid-latitude northwest Atlantic winter surface water temperatures are too low for this species and, therefore, *Globigerinoides sacculifer* is an indicator of summer and early fall conditions in this region (Tolderlund and Bé, 1971). Although coastal upwelling (Wooster et al., 1976) dominates the summer fauna along the Iberian coast and the western extreme of the Mediterranean, *Globigerinoides sacculifer* again is one of the summer species in the non-upwelling regions of the northeast Atlantic and western Mediterranean (cf. summer plankton haul data of Bé and Hamlin, 1967 and Cifelli, 1974 with winter data of Glacon et al., 1974 and Duprat, 1983).

The contemporaneous blooming of *Globigerinoides sacculifer* and *Globorotalia puncticulata* at many levels in the early Late Pliocene of Sicily (Fig. 6) can only be understood if *Globigerinoides sacculifer* represents the summer species and *Globorotalia puncticulata* the winter species. We, therefore, assert that the abundance fluctuations of both species in Fig. 6 reflect variations in summer and winter surface water temperature conditions in the early Late Pliocene of the Mediterranean.

Figure 6 also shows that both species are frequently absent over different periods of time. Since *Globigerinoides sacculifer* is the species which requires the highest surface water temperatures within this time-span at this location it seems reasonable to assume that whenever this species is absent, summer surface water

temperatures were too low. *Globorotalia puncticulata* on the other hand is the one which in the early Late Pliocene of Sicily requires the lowest surface water temperatures indicating that whenever this species is absent winter surface water temperatures were too high.

An R-mode analysis on the percent data of 16 categories (employing computer program BALANC which corrects for closed sum effects, Drooger, 1982) shows that *Globigerina falconensis* is the only one amongst the abundant categories that correlates negatively ($P < 0.01$) with *Globigerinoides sacculifer*. This suggests that *Globigerina falconensis* is a sensitive recorder of summer surface water temperatures that are too low for *Globigerinoides sacculifer*. The slightly different surface water temperature requirements of *Globigerina falconensis* and *Globigerinoides sacculifer* agree with their distribution in the modern ocean where *Globigerina falconensis* flourishes in cool-subtropical waters (Malmgren and Kennett, 1977; Van Leeuwen, 1988) while *Globigerinoides sacculifer* is abundant in tropical to warm-subtropical waters (e.g. Bé and Hutson, 1977).

Variations in Mediterranean surface water temperature 2.92 to 3.50 Ma

Abundance patterns of *Globigerinoides sacculifer*, *Globorotalia puncticulata* and *Globigerina falconensis* are dominated by short-term fluctuations of about 20 kyr (Fig. 6) and covary with precession-related variations in lithology. Peak-abundances of *Globigerinoides sacculifer* and *Globorotalia puncticulata* always correlate ($P < 0.01$) with the grey-coloured, carbonate-poor parts of the small-scale sedimentary cycles. This suggests that these layers correspond with higher summer and/or lower winter surface water temperatures than those of white layers. Consequently, seasonal contrasts might have been higher during the deposition of grey layers than during that of white layers.

The lower carbonate content in the grey-coloured parts of Early Pliocene cycles has been

linked to non-carbonate dilution brought on by a periodical increase in precipitation and subsequent supply of river-born fine-grained sediments (De Visser et al., 1989). If a similar mechanism holds true for the early Late Pliocene grey-coloured, carbonate-poor intervals then these intervals represent periods of increased seasonality and precipitation. The linkage of the small-scale sedimentary cycles to the equinoxial precession and of the grey layers to a higher seasonality, implies that the summer solstice occurred near perihelion during the deposition of grey layers. Obviously, this phase of the precession cycle is accompanied by an increase in regional precipitation.

Sapropelitic interbeds in the higher part of the section are intercalated in the grey-coloured parts of the small-scale cycles (Fig. 2) indicating that the phase-relationship with the precession cycle is the same for both facies types. Early Late Pliocene sapropelitic layers, therefore, were most likely deposited at times when the summer solstice occurred near perihelion, i.e. in periods with enhanced seasonality and precipitation. A similar relationship between a near-perihelion summer solstice and increased precipitation has been proposed by Rossignol-Strick (1983) to explain the formation of Late Quaternary sapropels in the Eastern Mediterranean.

Since precession-related grey layers extend back into the earliest Pliocene (Hilgen, 1987) there must be some process additional to external forcing to initiate the formation of sapropelitic layers in Sicily 2.94 Ma. Such a process, which most likely is a tectonic one, would make the basin setting suitable for the formation of sapropels.

Short-term variations in early Late Pliocene Mediterranean surface water temperature, thus, are primarily controlled by the equinoxial precession. Additional control by the obliquity cycle is evidenced by 35 kyr abundance fluctuations in *Globigerinoides sacculifer* 3.50 to 3.35 Ma (Fig. 6).

The most conspicuous long-term faunal

change is recorded by the abundance pattern of *Globorotalia puncticulata*. This species is permanently present, mostly in high percentages (Zachariasse and Spaak, 1983), from its first occurrence level at 4.13 Ma (Zijderveld et al., 1986) to 3.38 Ma (Fig. 6). At 3.38 Ma *Globorotalia puncticulata* vanishes and does not reappear until 3.16 Ma (Fig. 6). The vanishing of *Globorotalia puncticulata* between 3.38 and 3.16 Ma would indicate that at 3.38 Ma winter surface water temperatures began to rise above the maximum temperature requirement of this species and that winter surface water conditions remained relatively warm for the next 220 kyr. The prolonged absence of *Globorotalia puncticulata* is coincident with a long-term increase in peak-abundances of *Globigerinoides sacculifer* (Fig. 6). This long-term trend over-rides the short-term, astronomically controlled, abundance variations of *Globigerinoides sacculifer* and reflects an overall upward increase in maximum summer surface water temperatures that culminated at 3.18 Ma when *Globigerinoides sacculifer* reached highest percentage values of the entire Pliocene (cf. Zachariasse and Spaak, 1983). Sparse and scattered occurrences of *Globorotalia menardu* and *Neogloboquadrina dutertrei* between 3.38 and 3.18 Ma also indicate that summer surface water temperatures in the Mediterranean were occasionally sufficiently high to provide shelter for (possibly expatriated) individuals of truly tropical species.

The time between 3.38 and 3.18 Ma thus represents a period of high average winter surface water temperatures and of increasing maximum summer surface water temperatures. High surface water temperatures in the Mediterranean from 3.38 to 3.18 Ma agree with a relative high abundance of discoasters and a scarcity of geophyrocapsids in this region (Driever, 1988) but conflict with a postulated cooling in the mid-latitude North Atlantic at that time (Loubere and Moss, 1986; Raymo et al., 1987). Much of the evidence for a surface water cooling in the mid-latitude North Atlantic is based on the

prolonged absence of *Globorotalia puncticulata* in DSDP Sites 548 (Loubere and Moss, 1986) and 609 (Raymo et al., 1987), which is associated with increased percentages of the cold-tolerant *Neogloboquadrina atlantica*. The latter species is a Late Miocene to Late Pliocene species indigenous to the mid to high-latitude North Atlantic (Poore and Berggren, 1975a). The habitat of *Neogloboquadrina atlantica* most likely is in cool water and the areal extent of this species, therefore, might be controlled by cool surface water conditions. However, abundances of *Neogloboquadrina atlantica* within the area of distribution are not necessarily related to surface water temperatures, but — just as has been proposed for other neogloboquadrinids (Van Leeuwen, 1988) — they may be controlled by the total production in the photic layer. Therefore, we do not have to accept the postulated surface water cooling in the mid-latitude North Atlantic 3.4 to 3.2 Ma. Our data from the Mediterranean point to a warming between 3.38 and 3.18 Ma rather than to a cooling. Obviously, warm (winter) surface waters in the North Atlantic and Mediterranean expanded at 3.38 Ma and reduced the distribution of *Globorotalia puncticulata* to an area north of Site 609 for the next 220 kyr. This interpretation agrees with the persistent occurrence of *Globorotalia puncticulata* in the Late Pliocene at Rockall Bank (Poore and Berggren, 1975b; Spaak, 1981).

From 3.18 to 3.15 Ma abundances of *Globigerinoides sacculifer* drop to (near) zero values and remain that low until 3.03 Ma (Fig. 6). *Globorotalia puncticulata* reappears at 3.16 Ma and shows modest precession-related abundance variations until 3.02 Ma (Fig. 6). Obviously, summer and winter surface waters in the Mediterranean rapidly cooled from 3.18 to 3.15 Ma and remained cool until about 3.03 Ma (Fig. 6).

Cooling of Mediterranean surface waters at 3.18 Ma is consistent with an increase in geophyrocapsids and a concomitant decrease in discoasters in the Mediterranean (Driever, 1988), also with a change from warm to cool

planktonic foraminiferal faunas (Ehrmann and Keigwin, 1987), and with an enrichment in $\delta^{18}\text{O}$ (Keigwin, 1987) within the lower part of the Mammoth subchron in the North Atlantic DSDP Site 606. In the Caribbean, 3.2 Ma cooling conditions are marked by the arrival of *Globorotalia puncticulata* (Keigwin, 1982b), while Prell (1984) recognized a brief increase in $\delta^{18}\text{O}$ values in all three major oceans at about 3.2 Ma. Climatic cooling conditions at 3.18 Ma thus seem to be ubiquitous. However, since first unequivocal evidence for ice-rafting in the North Atlantic does not occur before 2.55 Ma (Rudiman et al., 1987b) there is considerable uncertainty to what extent these cooling conditions are associated with Northern Hemisphere continental ice growth (Shackleton and Opdyke, 1977; Keigwin and Thunell, 1979; Keigwin, 1982a) or with cooling of high-latitude surface water and production of colder bottom water (Backman, 1979; Thunell and Williams, 1983; Prell, 1984).

Recently, Keigwin (1987) attributed the excess enrichment in $\delta^{18}\text{O}$ values of benthic foraminifers over those of planktonic foraminiferal carbonate to a cooling of NADW in addition to a small glacial advance. Evidence for Northern Hemisphere continental ice growth at that time is furnished by a recalculated age of 3.18 Ma (Mankinen and Dalrymple, 1979) for the oldest tills in Iceland (McDougall and Wensink, 1966) and suggests that climatic cooling at 3.18 Ma most likely is related to the initiation of Northern Hemisphere ice growth.

The onset of Northern Hemisphere ice growth has long been associated with the emergence of the Panama Isthmus (e.g. Berggren and Hollister, 1977; Keigwin, 1978). The reason is that a closure of the Pacific connection would strengthen the Gulf Stream (Berggren and Hollister, 1977) causing warm surface waters to penetrate into higher latitudes and supply moisture necessary for initiating continental ice accumulation (Keigwin and Thunell, 1979).

Prolonged high winter surface water temperatures in the Mediterranean from 3.38 to 3.16 Ma coupled with a prolonged increase in maximum summer surface water temperatures culminating at 3.18 Ma could indeed reflect a progressive strengthening of the Gulf Stream. A more vigorous Gulf Stream would inject larger volumes of warm surface water into the North Atlantic Drift and eastern boundary current, thus warming surface waters in the mid to high-latitude northeast Atlantic and Mediterranean. Strengthening of the Gulf Stream at 3.38 Ma suggests that the closure of the Isthmus of Panama was not completed before that time and this agrees rather well with the severed faunal interchange between the Atlantic and Pacific oceans 3.3 to 3.0 Ma (Keigwin, 1982b). The transport of larger volumes of warm surface water via the North Atlantic Drift into high latitudes might have subsequently stimulated high-latitude snow-fall, but whether snow-fall alone is sufficient to initiate Northern Hemisphere continental ice seems doubtful. As long as the snow cover melts off during summer, no net accumulation of snow will take place and thus no continental ice-sheet will form. Critical for a net accumulation of snow is a minimum summer insolation (Milankovitch, 1930; Weertman, 1976). Minimum summer insolation at Northern Hemisphere high-latitudes is attained during periods in which the summer solstice shows a maximum sun-earth distance with obliquity values at a minimum and we suggest that these conditions prevailed at 3.18 Ma. Once the net accumulation of snow changed to positive, continental ice could grow rapidly by the ice-albedo feedback.

The short-term enrichment in $\delta^{18}\text{O}$ of planktonic and benthic foraminiferal carbonate in the mid-latitude North Atlantic indicates that the glacial advance at 3.18 Ma is temporary (Keigwin, 1987) suggesting a waning of continental ice shortly after initial growth.

Also in the Mediterranean summer and winter surface waters remained cool for a short period between 3.18 and 3.03 Ma (Fig. 6). In-

creased abundances of *Globigerinoides sacculifer* at 3.03 Ma suggest that summer surface water conditions in the Mediterranean ameliorated at that time, whereas winter surface water temperatures kept falling as is evidenced by the increasing percentages of *Globorotalia puncticulata* (Fig. 6). Thus at about 3.03 Ma seasonal contrasts steepened and this increase in seasonality might be attributable to an increase in orbital eccentricity. Increased eccentricity values and associated higher summer insolation at Northern Hemisphere high-latitudes at 3.03 Ma could possibly explain why continental ice growth diminished shortly after its initiation at 3.18 Ma.

Conclusions

Paleomagnetic measurements on samples from 100 stratigraphic levels in the early Late Pliocene of Sicily provides an unprecedented high-quality polarity sequence which extends from the upper reversed Gilbert to the upper normal Gauss subchron. The resultant chronology for the early Late Pliocene provides ages for the following principal Mediterranean bioevents:

1	FOD <i>Globorotalia crassaformis</i>	3.40 Ma
2	prolonged absence of <i>Globorotalia puncticulata</i>	3.38–3.16 Ma
3	LOD <i>Uvigerina rutila</i>	3.16 Ma
4	LOD <i>Sphaeroidinellopsis seminulina</i>	3.07 Ma
5	LOD <i>Globoquadrina altispira</i>	3.04 Ma
6	LOD <i>Cibicides italicus</i>	2.96 Ma

Short-term variations in temperature of the surface water and in colour and carbonate content of the sediment are primarily controlled by the equinoxial precession. Higher summer and/or lower winter surface water temperatures are always associated with grey-coloured, carbonate-poor layers suggesting that the seasonality is higher during the deposition of the grey-coloured layers than during that of the white-coloured facies. A higher seasonality during the grey-coloured facies suggests that at that time the summer solstice was near perihelion,

whereas an inverse alignment occurred at the time of deposition of the white layers. This phase-relationship between the precession cycle and grey-coloured layers also applies for the sapropels which began to intercalate in the grey-coloured facies at 2.94 Ma.

Long-term changes in surface water temperatures include a warming between 3.38 and 3.18 Ma followed by a cooling from 3.18 to 3.03 Ma. At 3.03 Ma summer and winter surface water temperatures started to diverge which suggests an increase in seasonality, possibly as a consequence of an increase in orbital eccentricity. The warming of Mediterranean surface waters at 3.38 Ma is believed to be associated with the final elevation of the Isthmus of Panama. Consequent strengthening of the Gulf Stream injected larger volumes of warm surface water into the North Atlantic Drift and eastern boundary current. Thus surface waters warmed in the mid to high-latitude northeast Atlantic and Mediterranean. Surface water warming in the high latitude northeast Atlantic could have stimulated high-latitude snow-fall but to build-up continental ice requires a net accumulation of snow which can be achieved by lowering the summer insolation. We believe that minimum values of summer insolation at 3.18 Ma triggered the net accumulation of snow. The increased ice-albedo feedback enabled a first and rapid expansion of Northern Hemisphere continental ice thus cooling surface waters in the northeast Atlantic and Mediterranean.

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