Abrupt cold spells in the northwest Mediterranean

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Abstract. Hitherto unknown abundance peaks of left coiling (l.c.) *Neogloboquadrina pachyderma* from a Gulf of Lions piston core indicate that abrupt cold spells associated with Atlantic Heinrich events affected the Mediterranean. *N. pachyderma* (l.c.) is typical of (sub) polar waters in the opean ocean. The southern edge of its glacial North Atlantic bioprovince reached south Portugal. Only trace abundances of *N. pachyderma* (l.c.) are known from Quaternary Mediterranean sediments, suggesting that no significant "invasions" occured via the Strait of Gibraltar. The Gulf of Lions abundance peaks therefore seem to reflect area-specific thriving of a normally rare but indigenous taxon in the western Mediterranean through local favorable habitat development. The general planktonic foraminiferal record suggests that the basic hydrographic regime in the Gulf of Lions, with wintertime deep convective overturn, was relatively stable over the past 60 kyr. Under these conditions, high abundances of *N. pachyderma* (l.c.) would essentially imply temperature reductions of the order of 5°-8° relative to the present.

1. Introduction

Heinrich events of ice-rafted debris (IRD) deposition are widespread throughout the North Atlantic [e.g., *Heinrich*, 1988; *Bond et al.*, 1992, 1993; *Grousset et al.*, 1993]. The iceberg armadas responsible for the IRD deposits occurred at the cold apex of so-called Bond cycles of gradual cooling and rapid warming on a 7-13 kyr timescale [*Bond et al.*, 1993; *Broecker*, 1994]. Intense coolings over Europe during Heinrich events suggest substantial southward expansion of polar air masses [e.g., *Guiot et al.*, 1993].

No repeated events with time equivalence to these Atlantic/European coolings have yet been described for the Mediterranean Sea. However, especially the western Mediterranean should be highly sensitive to (1) an oceanic influence via the Atlantic surface water inflow through the Strait of Gibraltar and/or (2) a climatic influence through more frequent and intense outbursts of cold air over the basin at times of southward expansion of polar air masses over Europe. Orography channels cold air flows in the wake of westward tracking Atlantic depressions toward the Mediterranean, and resultant outbursts of cold and dry air through the Rhone valley are key to circulation in the Gulf of Lions and deep western Mediterranean [*Leaman and Schott*, 1991] (Figure1).

Provisional confirmation that climatic/oceanic changes associated with Heinrich events did affect the Mediterranean

came from recent descriptions of a sharp 15-12.5 ka B.P. cooling event in the western Mediterranean [*Kallel et al.*, 1997a,b]. It remains to be demonstrated, however, whether such events are repeated with similar timing as Heinrich events, and if so, a plausible linking mechanism needs to be established. For that purpose we here present results for Core BC15 from the Gulf of Lions (Figure 1).

2. Material, Methods, and Time-Stratigraphic Framework

Core BC15 (41°57' N, 05°56' E; 2500 m water depth) consists of clay to fine silt-sized sediments that alternate with a considerable number of distinct, thin, sandy turbidites (Figure 2). Since distinct turbidites are present we need to consider the possible presence of additional (undetected) turbidites and/or of erosional hiatuses at the base of turbidites. Such features would show as irregularities in a sufficiently detailed time-stratigraphic framework. The time frame for BC15 is based on biostratigraphy, isotope stratigraphy, and accelerator mass spectrometry (AMS)[14]C dating.

A total of 91 samples was dried (24 hours; 50°C), weighed, soaked, and wet sieved with demineralized water into size fractions 63-150, 150-600, and >600 µm. Sieve residues were dried (50°C) and weighed. A random splitter produced statistically representative splits from the 150-600 µm size fraction for the various analyses. Total planktonic foraminiferal assemblages were quantified in relative abundances (percent) from splits containing ≥200 specimens for 56 of the samples. Three conspicuous biostratigraphic levels allow correlation to previous well-dated studies. Absolute abundances (numbers g[-1] dryweight) were determined to check for disruptive closed sum effects. We concentrate on percentages of left (l.c.) and right coiling (r.c.) *Neogloboquadrina pachyderma* relative to total planktonics and also of left coiling relative to total *N. pachyderma* from separate representative splits of all samples.

The $\delta^{18}O$ record is based on 77 successful analyses of 5-10 clean specimens per sample of *N. pachyderma* (r.c.). The size range of 250-350 µm was constrained by measurement of each

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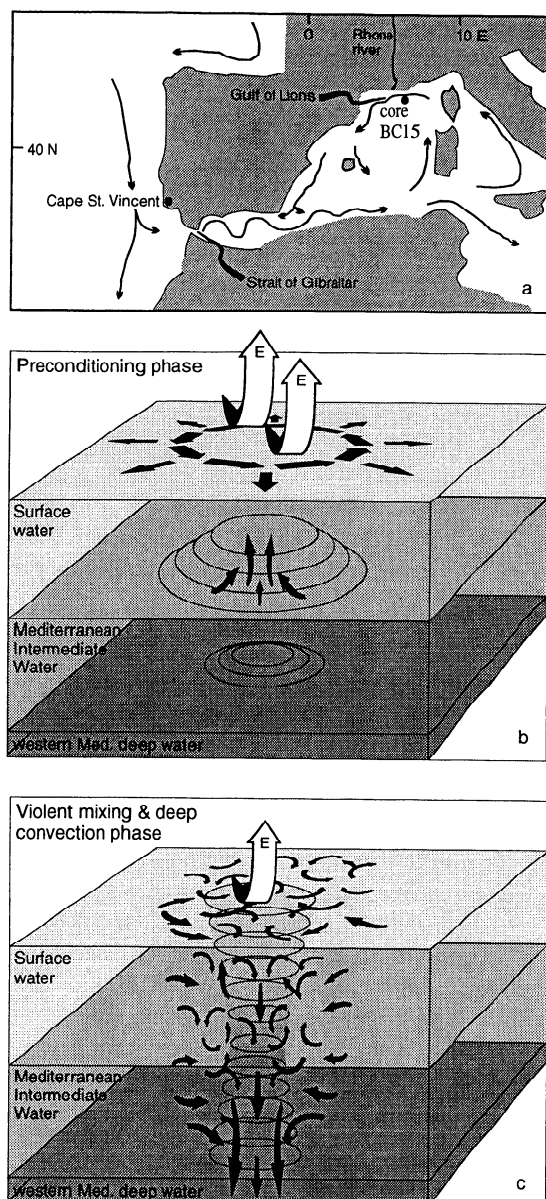
Figure 1. (a) Location map for Core BC15 with schematic indication of general surface water circulation (arrows); (b) schematic representation of processes in the Gulf of Lions during the preconditioning phase of deep water formation. E indicates evaporation; arrows indicate general flow directions. Precondioning precedes late February/early March deep convective overturn that forms Western Mediterranean Deep Water (WMDW). Main buoyancy loss is through evaporation and cooling due to southward excursions of dry and cold air masses (in the wake of westward tracking Atlantic depressions) that are orographically channeled toward the Gulf of Lions. During preconditioning, strong surface buoyancy loss (1) intensifies cyclonic surface water circulation, causing doming of the warm and salty intermediate water from a normal depth of 200-250 m to < 100 m and (2) reduces the surface to intermediate water density contrast. Then follows (c) violent mixing of surface and intermediate waters, which results in the formation of a water mass of greater density, WMDW, which spreads to depths over 2000 m. Figures 1b and 1c and process decriptions are after MEDOC-group [1970], Lacombe et al. [1984] and Leaman and Schott [1991].

specimen's longest axis under the microscope, which gives more accurate control than dry sieving [Kroon and Darling, 1995].

AMS[14]C datings (Utrecht University) are based on 10-15 mg clean planktonic foraminiferal carbonate (Table 1). Although small sample sizes mostly inhibited monospecific extraction of the required carbonate mass, one dating (27.38 ± 0.24 ka B.P. [14]C) does represent a virtually monospecific sample of N. pachyderma (l.c.), minimising bioturbation effects since this species is virtually absent above and below the dated peak. In the other three datings, bioturbation effects may have more in-fluence, but generally high sedimentation rates (see below) limit this problem. Following Bard [1988] and Broecker et al. [1988], raw dating results (labelled ^{14}C) are "corrected" for a reservoir age of 400 yr (giving ages labeled [14]C_c). Although this value might be up to 135 years too high [Stuiver and Brazunias, 1993], it is used to facilitate comparison with previous [14]C_c ages
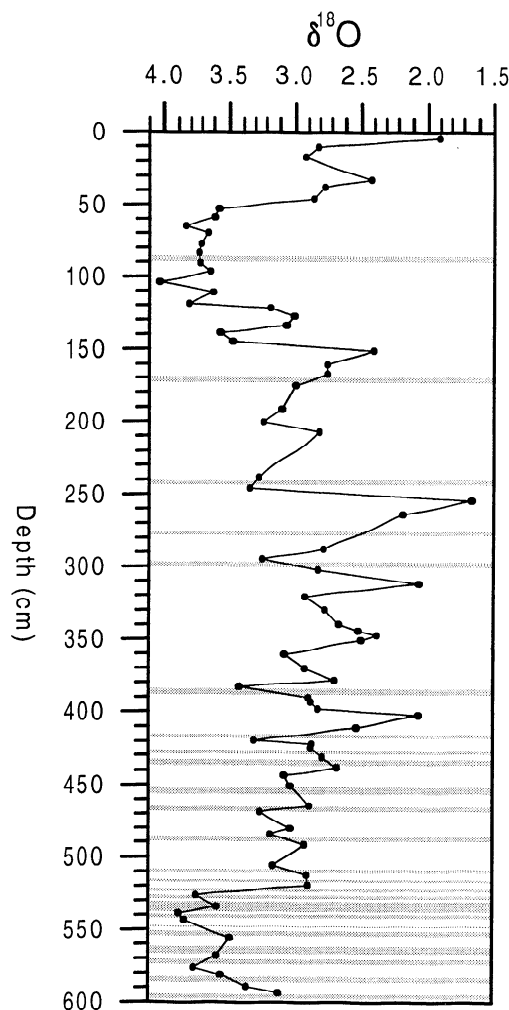
Figure 2. Schematic representation of the core lithology. White indicates normal hemipelagic clay to fine silt sized sediments; shaded bands indicate distinct, thin, sandy turbidites. Also shown is the $\delta^{18}O$ record based on right coiling Neogloboquadrina pachyderma (in per mill relative to Pee Dee belemnite (PDB) standard) relative to core lithology.

Table 1. Dating Control Points for Core BC15, Gulf of Lions

Event/Code	Depth, cm	^{14}C, ka B.P.	Mean $^{14}C_c$ Reservoir Age - 400 years	Mean Calender Age, ka B.P.	Notes[a]
		AMS^{14}C			
UTC4468 4.25	10.15 ± 0.080	9.75	10.99	a	
UTC4469 64.75	14.67 ± 0.090	14.27	17.11	a	
UTC4470 175.25	27.38 ± 0.240	26.98	31.2	b	
UTC4470 256.25	31.60 ± 0.400	31.2	34.4	b	
		Isotope Stratigraphy			
End T1b	4.25		9.2[b] / 9.4[c] / 9.5[d]	10.3 / 10.5 / 10.8	a
Onset deglaciation	64.75		14.5[e] / 14.6[c]	17.4 / 17.5	a
Stage 2/3 boundary (3.0)	117.25			24.0[f]	c
Event 3.1 127.25			25.4[f]	c	
Stage 3/4 boundary (4.0)	475.75			59.0[f]	c
		Biostratigraphy			
Exit *Globorotalia scitula* and peak *Globorotalia truncatulinoides*	32.25	~13.0[c]	~12.6	~14.8	a
Entry *Globorotalia inflata*	37.75	~14.0[c]	~13.6	~16.3	a
Exit *G. inflata*	229.75		~30[g] / ~36[h]	~33 / ~39	b

[a] Notes are a, ages <22 ka B.P., radiocarbon ages (^{14}C) converted into calendar years (Cal) with program Calib3.03 [*Stuiver and Reimer*, 1993] using calibration data set 3 and with Δr = 0 since we infer a reservoir age of 400 years; b, ages >22 ka BP, a lack of calibration allows only a minimum conversion using a constant offset of ~ +3.2 kyrs, i.e., the difference between $^{14}C_c$ and calendar years at 22 ka BP [*Manighetti et al.*, 1995]; and c, No conversion needed as date was obtained in calendar years through orbital tuning [*Martinson et al.*, 1987].

[b] *Fairbanks* [1989]
[c] *Jorissen et al.* [1993]
[d] *Duplessy et al.* [1986]
[e] *Pujol and Vergnaud-Grazzini* [1989]
[f] *Martinson et al.* [1987]
[g] *Rohling et al.* [1993]
[h] *Muerdter and Kennett* [1983/84]

based on a 400 year value (Table 1). Where appropriate, ^{14}C ages were converted into calendar ages (labeled Cal) (see Table 1 for details).

An age-depth plot is constructed, with all ages standardised to calendar years (Table 1 and Figure 3), to (1) allow a combination of orbitally tuned ages for isotope events (calendar years) with radiocarbon results and (2) assess changes in "background" (non turbidite) sedimentation rates without distortion by ^{14}C platforms. For the same reason the depth scale concerns sample positions after substraction of the geologically instantaneously deposited turbidites. Linear regression (R^2 = 0.98) indicates a stable background sedimentation rate of 9.7 cm kyr^{-1} (Figure 3). We infer that no significant mass deposition or erosion events have been overlooked.
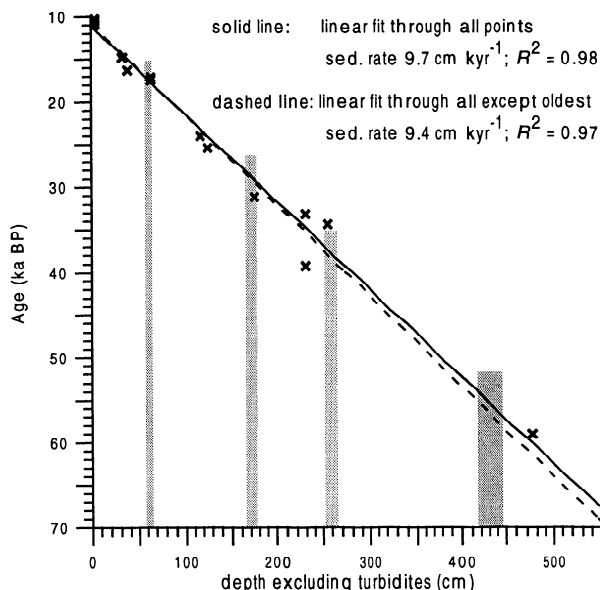
Figure 3. Age-depth plot for Core BC15. All ages are in calendar years (see Table 1). Depth is measured from core top (= 0 cm), while thicknesses of the intercalated, distinct, sandy turbidites are subtracted. Shading indicates positions of the left coiling *N. pachyderma* abundance peaks in Core BC15. The two linear fits, one dependent and the other independent of the oldest data point, are very similar and indicate a stable background sedimentation rate of 9.7 cm kyr^{-1}.

## 3. General Variations in the Planktonic Fauna

The planktonic foraminiferal record shows a stable species composition throughout BC15 (Figure 4), with continuous dominance of *Globigerina bulloides* with *Turborotalita quinqueloba*, *N. pachyderma* and *Globogerinita glutinata*. In the upper 50 cm, *Globorotalia inflata* becomes more important while *G. bulloides* and *T. quinqueloba* are reduced. A distinct increase can also be seen in the warm subtropical species *Globigerinoides ruber*, which today thrives in the summer mixed layer. Although the Holocene is not represented (Figure 3), faunas in the uppermost samples already bear much similarity to that living in the area at present, dominated by *N. pachyderma* with *G. bulloides* and *G. inflata* [*Pujol and Vergnaud-Grazzini*, 1995; *Rohling et al.*, 1995]. Today, winter eutrophication through nutrient up mixing from deep waters is the main determinant of foraminiferal abundances [*Pujol and Vergnaud-Grazzini*, 1995]. The observed continuity in overall faunal composition throughout BC15 suggests that the Gulf of Lions experienced a modern-type hydrographic regime throughout the last glacial cycle with deep convective overturn and its inherent eutrophicating influence. Superimposed fluctuations seem to have occurred in sea surface temperature and related summer stratification.

In more detail a presence-absence pattern shows in the record of *G. inflata* and in the opposite sense also in *Globorotalia scitula*. These patterns correlate with previous Mediterranean biostratigraphies [*Muerdter and Kennett*, 1983/84; *Jorissen et al.*, 1993; *Rohling et al.*, 1993], and so provide three "dated" levels for core BC15 (Table 1).

N. pachyderma (l.c.) occurrences appear not to be restricted to periods of high total *N. pachyderma* abundances (Figures 4 and 5), suggesting that the habitats of the two coiling types are not identical but separated in either space or time. *N. pachyderma* (r.c.) thrives during the preconditioning phase before deep convective overturn (Figure 1b), when updoming intermediate water eutrophicates the base of the euphotic layer [*Rohling et al.*, 1995]. Below we propose that *N. pachyderma* (l.c.) instead proliferated during or just after the deep convective phase, at times when its preferred temperature conditions were met.

4. Ages of Left Coiling *N. pachyderma* Intervals

The upper three intervals with enhanced *N. pachyderma* (l.c.) abundances were directly AMS^{14}C dated (Table 1 and Figure 5). Results of 14.27 ± 0.09 and 26.98 ± 0.24 ka B.P. $^{14}C_c$ for the two youngest peaks suggest synchroneity with Heinrich-events
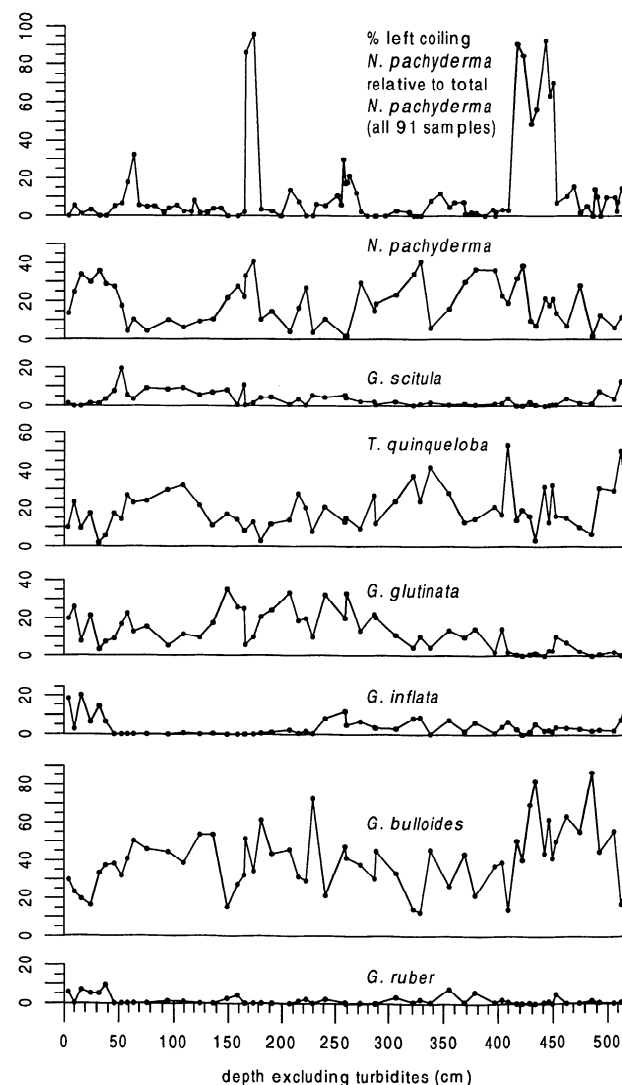
Figure 4. Downcore plots of relative abundances (percent) of the main planktonic foraminiferal species in Core BC15 and (right-hand side) percentage of left versus right coiling *N. pachyderma*.
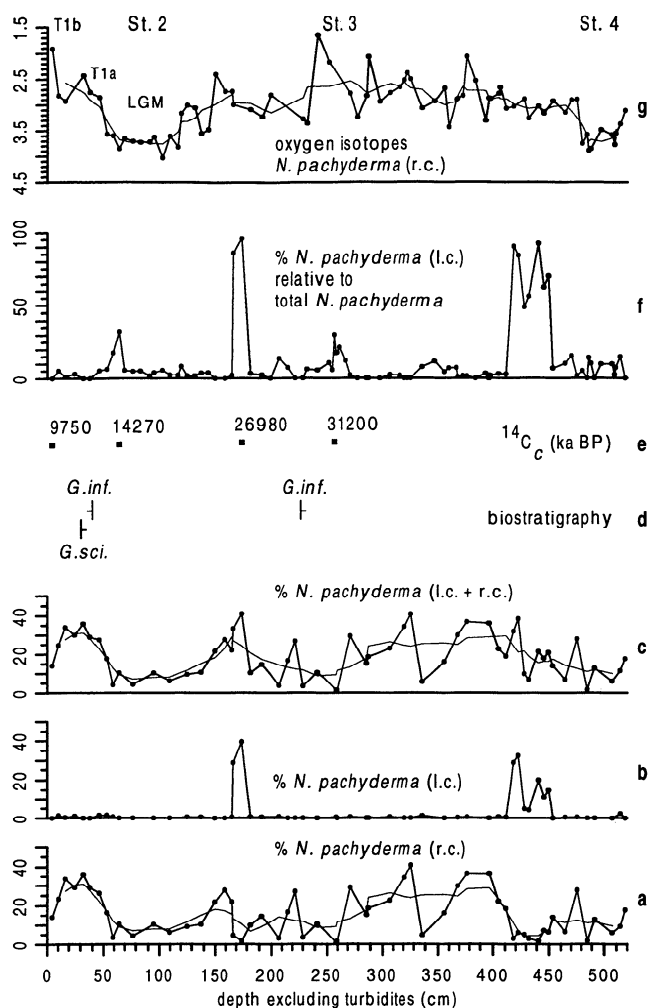
Figure 5. (a) Relative abundances of right coiling *N. pachyderma* with repect to the total planktonic foraminiferal assemblage in Core BC15; (b) relative abundances for left coiling *N. pachyderma*; (c) relative abundances for the sum of left and right coiling *N. pachyderma*; (d) positions of the three distinct biostratigraphic levels used in the construction of the time-stratigraphic framework (see Table 1); (e) positions and mean values of the four accelerator mass spectrometry (AMS)[14]C datings (see Table 1); (f) percentage of left coiling *N. pachyderma* with respect to total (left and right coiling) *N. pachyderma*; and (g) oxygen isotope ($\delta^{18}O$) record. The abbreviations are defined as: *G. sci* (bar with upward tick), exit *Globoro-talia scitula*; *G. inf* (bar with downward tick), exit *Globorotalia inflata*; *G. inf* (bar with upward tick), entry *Globorotalia inflata* (see also Figure 4); T1a, termination 1a; T1b, termination 1b; LGM, last glacial maximum; and St.2, St.3, and St.4, oxygen isotope stages 2, 3, and 4 respectively. Thin lines through records are five point moving averages, showing general trends.

H1 and H3 in the Atlantic [*Grousset et al.*, 1993; *Bond et al.*, 1992; *Zhao et al.*, 1995; *Stoner et al.*, 1996; *Vidal et al.*, 1997]. The dating of 31.2 ka B.P. $^{14}C_c$ for the third interval is slightly young compared with H4 (33-36 ka B.P. [*Bond et al.*, 1993; *Stoner et al.*, 1996; *Cortijo et al.*, 1997; *Vidal et al.*, 1997]). It is also young with respect to the calendar age of ~38 ka B.P. Cal suggested by the regression line in our age model (Figure 3), which corresponds to a radiocarbon age of ~35 ka B.P. $^{14}C_c$,

similar to that of H4. The lowermost *N. pachyderma* (l.c.) peak in BC15 is too old for radiocarbon dating, but the age - model suggests a calendar age around~55 ka B.P. Cal, near that of H5 [*Grousset et al.*, 1993; *Manighetti et al.*, 1995; *Zhao et al.*, 1995; *Stoner et al.*, 1996].

We infer that within the limits of our age assessment for BC15 the most notable peaks of *N. pachyderma* (l.c.) in BC15 cor-respond to Heinrich events H3 and H5, while the minor peaks of *N. pachyderma* (l.c.) correspond to H1 and H4. More extensively dated studies are needed to establish exact phase relationships.

5. Implications for Sea Surface Temperature

N. pachyderma (l.c.) dominates planktonic foraminiferal faunas where the maximum sea surface temperature (maxSST) is below 7°C [*Ericsson*, 1959; *Bé and Hamlin*, 1967; *Reynolds and Thunell*, 1986] and often forms a major faunal element where maxSST ≤ 14°C [*Giraudeau*, 1993; *Ufkes and Zachariasse*, 1993]. Low but significant numbers are known from (seasonally) productive waters with maxSST ≤ 17°C [*Duprat*, 1983; *Giraudeau*, 1993]. All areas where the taxon prevails have high phytoplankton abundances in common fueled by intensive mixing and consequent nutrient availability as found both in upwelling cells [*Giraudeau*, 1993; *Ufkes and Zachariasse*, 1993] and (sub)polar waters [*Ericsson*, 1959; *Bé and Hamlin*, 1967; *Reynolds and Thunell*, 1986]. Ecosystems in such settings lack the habitat separation and specialization that support the more diverse faunas observed in stably stratified (sub)tropical waters [*Tolderlund and Bé*, 1971]. We infer that *N. pachyderma* (l.c.) is an opportunist that inhabits a variety of (seasonally) eutrophi-cated settings, bound by relatively low temperature limits.

During the last glacial maximum the bioprovince of *N. pachyderma* (l.c.) extended southward to Cape St. Vincent (south Portugal) [*Duprat*, 1983]. No distinct invasions into the Mediterranean are known; it exists only in trace abundances (<2%) in late Quaternary western Mediterranean sediments [*Duprat*, 1983; *Pujol and Vergnaud-Grazzini*, 1989; *Rohling et al.*, 1995; *Fraser*, 1997; *Mutch*, 1997]. Hence the strong H3 and H5 equivalent abundance peaks in the Gulf of Lions seem to reflect area-specific thriving of a normally rare but indigenous taxon in response to temporary development of favorable habitat conditions. These would consist of seasonal high productivity (due to deep mixing driven surface water eutrophication [cf. *Béthoux*, 1989]) with maxSST ≤ 14°C. The weaker H1 and H4 equivalent peaks would reflect similar conditions with maxSST≤ 17°C.

Today, maxSST in the Gulf of Lions is 22°C (summer), and winter SST is 13°C [*Levitus*, 1982]. Therefore we infer that summer SST in the Gulf of Lions was lowered by ≥8°C during Heinrich events H3 and H5 and by ≥5°C at times of H1 and H4, relative to the present. These figures agree with estimated glacial annual temperature reductions of 6°ë11°C for southern France, with these being 1°ë3°C more intense in winter than in summer [*Guiot et al.*, 1993; *Bigg*, 1994].

A new Mediterranean foraminiferal modern analogue technique (MAT) offers scope for further comparison [*Kallel et al.*, 1997a,b]. It shows an SST drop of 6°C (relative to the

present) around H1 times in the Tyrrhenian Sea [*Kallel et al.*, 1997b], which agrees with our inferred reduction of 5°ë8°C in the Gulf of Lions. Unfortunately, the MAT cannot be used on Core BC15 since no modern Mediterranean analogues exist for the glacial faunas with abundant *G. scitula* or for those with abundant *N. pachyderma* (l.c.). It would seem inappropriate to use extra-Mediterranean analogues since the general Mediterranean oligotrophy might impose a shift of the assemblages' main sensitivity from SST (as in the open ocean) to productivity [*Pujol and Vergnaud-Grazzini*, 1995]. Such basin-specific habitat adaptation seems likely in view of recent planktonic foraminiferal DNA analyses, which show considerable genetic divergences between similar morphotypes from different water masses (*K. F. Darling et al.*, manuscripts in preparation, 1998).

6. Concluding Remarks

During Heinrich events, polar water masses extended as far south as 45° - 40°N in the Atlantic [*Grousset et al.*, 1993; *Robinson et al.*, 1995]. Southward expansion of polar air masses over the European continent caused strong cooling events at H1, H2, and especially H3 times superimposed on general glacial cooling [*Guiot et al.*, 1993; *Bigg*, 1994]. Our results suggest that closer proximity of polar air to the Mediterranean during Heinrich events facilitated more frequent and intense cold outbreaks over the Gulf of Lions, which reduced annual

temperatures by ≥5°ë8°C to values within the tolerance limits of *N. pachyderma* (l.c.). This normally rare but indigenous species, in turn, developed to peak abundances sustained by phytoplankton blooms fueled by the nutrients transferred to surface waters by seasonal deep convective mixing.

The inferred cold spells in the Gulf of Lions, the key site of Western Mediterranean Deep Water formation, must have affected deep water properties and the intensity of the basin's thermohaline circulation. The deep water consequences of our hypothesis may be verified using high-resolution benthic paleo-proxy records, while exact phase relationships between the Northwest Mediterranean and North Atlantic cold spells may be established by targeted coring and extensively dated high-resolution investigations.

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