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Abrupt hydrographic change in the Alboran Sea (western Mediterranean) around 8000 yrs BP

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Abstract—This paper discusses planktonic foraminiferal fauna results from the Alboran Sea, western Mediterranean. In this new record, as well as in previously published records, a rather abrupt faunal change occurs around 8000 BP, from dominance of *Neogloboquadrina pachyderma* (dextrally coiled) with *Globigerina bulloides*, to dominance of *Globorotalia inflata* with *Globigerina bulloides*. The paper argues that this change marks the onset around that time of more or less modern conditions with distinct geostrophic fronts separating the jet of Atlantic inflow from ambient Mediterranean waters. According to a previously published hydraulic control model for the Strait of Gibraltar with variable sea level, the inflow volume of Atlantic water around 8000 BP (sea level at about −30 m) may have amounted to a maximum of about 86% of its present value. Our reconstruction suggests, therefore, that the modern front-dominated conditions in the Alboran Sea prevail only when the inflow volume is at least 86% of the present volume, which should be confirmed in realistic models of the circulation through the Strait of Gibraltar and in the Alboran Sea.

INTRODUCTION

In this paper, we discuss a marked change in the planktonic foraminiferal record of the Alboran Sea (western Mediterranean; Fig. 1) as found in our analyses of core KS310 (35°55N, 1°34.5W, depth 1900 m) (Figs 2 and 3). This change is consistent with that reported in cores KS8232, 8231, 8230 and 8241 (Pujol and Vergnaud-Grazzini, 1989). The downcore foraminiferal percentages and numbers per gram dryweight for the upper 2 meters of core KS310 (i.e. last 20,000 years) have been put in a time-stratigraphic framework according to the age assignments to specific fauna events by Pujol and Vergnaud-Grazzini in core KS8232, which was recovered close to the site of KS310 (Fig. 1). Those authors provided such a framework for Alboran Sea cores on the basis of stable isotope stratigraphy supplemented by several ^{14}C dates (a total of 18 in the four cores they discussed, of which three were in KS8232), using linear interpolation between the dated "control-points".

In the Alboran Sea record of the past 20,000 years, planktonic foraminiferal assem-

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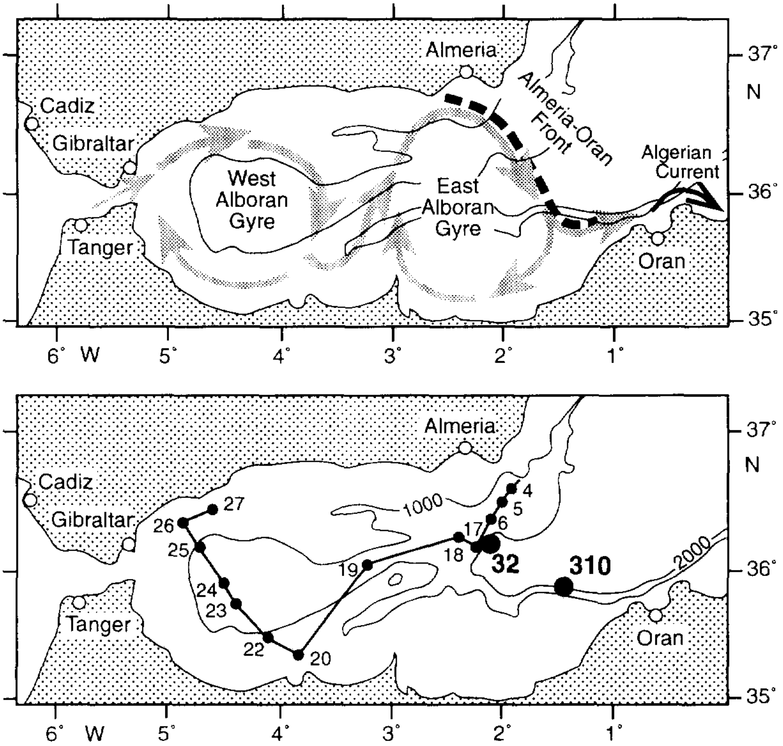

Fig. 1. Map of the Alboran Sea with the locations of cores KS310 (this study) and core KS8232 (Pujol and Vergnaud-Grazzini, 1989). Also indicated is the track map of plankton tows across the Alboran Sea from which the abundances of *G. inflata* in Fig. 5 are derived. The circulation pattern indicated is a very schematical representation of a fully developed two-gyre configuration (after Arnone *et al.*, 1990).

blages dominated by *Neogloboquadrina pachyderma* (dextrally coiled) with *Globigerina bulloides* are replaced around 8000 BP by assemblages dominated by *Globorotalia inflata* with *Globigerina bulloides* (see Figs 2 and 3). To assess the cause of this transition, we discuss the modern habitats of the species involved in the western Mediterranean. This provides us with a likely explanation for the marked Alboran Sea-wide faunal change in terms of the intensity of Atlantic inflow through the Strait of Gibraltar, which has changed as a function of post-glacial sea level rise and variations in net evaporation.

RECENT CIRCULATION IN THE ALBORAN SEA

Especially during the last two decades, the Alboran Sea has received ample oceanographic attention, with support from remote sensing techniques. This interest is due partly to the key role of its hydrography in studies concerned with exchange transports through the Strait of Gibraltar (Stommel *et al.*, 1973; Roether and Weiss, 1975; Gascard and Richez, 1985; Pistek *et al.*, 1985; Parilla *et al.*, 1986; Richez and Gascard, 1986; Kinder and Parilla, 1987; Minas *et al.*, 1991), and partly to the distinct presence of major oceanic front-systems (Cheney and Doblar, 1982; Tintoré *et al.*, 1988; Arnone *et al.*, 1990; Heburn and

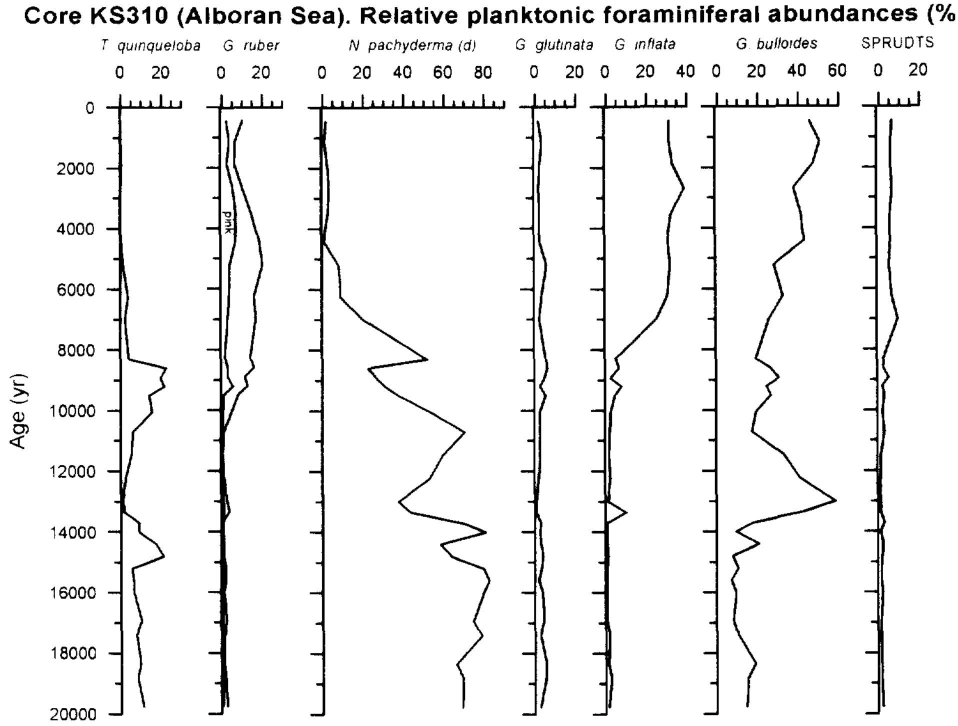

Fig. 2. Percentages of the various planktonic foraminiferal species in core KS310 versus age (^{14}C years). SPRUDTS-group is the sum of the infrequent species *G. siphonifera*, *H. pelagica*, *G. rubescens*, *O. universa*, *G. digitata*, *G. tenella* and *G. sacculifer*.

La Violette, 1990; Perkins and Pistek, 1990; Prieur *et al.*, 1993; Prieur and Sournia, 1994; Claustre *et al.*, 1994).

The latter studies together portray the dynamics of the geostrophic frontal systems that separate the jet-like structure of Atlantic inflow from the ambient Mediterranean water. The Atlantic inflow commonly forms two anti-cyclonic eddies within the Alboran Sea, and although both may apparently disappear for short periods of time, this never seems to happen for both at the same time (Heburn and La Violette, 1990). Although it is therefore hard to identify any one gyre configuration as "normal", we have included a sketch of a fully developed two-gyre circulation in the base map (Fig. 1) for comparison with the core locations and plankton tow stations discussed in this paper.

The most pronounced front is found generally in the eastern part of the Alboran Sea, between Almeria (Spain) and Oran (Algeria), and is consequently called the Almeria–Oran front (Fig. 1). Although the Almeria–Oran front was less distinctly developed during their study, Prieur *et al.* (1993) found direct influence of the frontal system on production, as evidenced by chlorophyll *a* contents in the upper 150 m of 60–100 mg m^{-2}, more than three times higher than expected on the basis of the general oligotrophy of the ambient water masses. The authors furthermore argued that distinct upwelling and downwelling occur in association with the front, in a secondary circulation through the jet core, which supports such inferences for the Almeria–Oran front by Tintoré *et al.* (1988) and Claustre *et al.* (1994) and for the Ligurian Sea by Boucher *et al.* (1987) and Sournia *et al.* (1990).

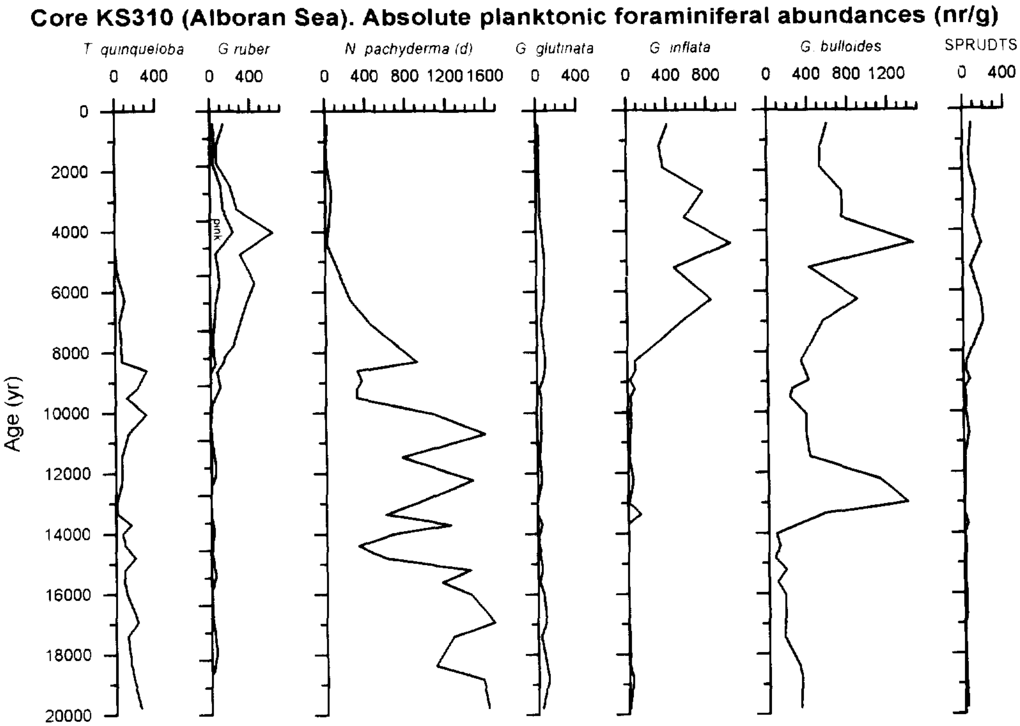

Fig. 3. Numbers per gram of the various planktonic foraminiferal species in core KS310 versus age (^{14}C years). SPRUDTS-group is the sum of the infrequent species of *G. siphonifera*, *H. pelagica*, *G. rubescens*, *O. universa*, *G. digitata*, *G. tenella* and *G. sacculifer*.

Prieur and Sournia (1994) argued that the Almeria–Oran front may be considered to be a permanent feature, but that its position and intensity depend on the development of the eastern anticyclonic gyre in the Alboran Sea, illustrated clearly by the approximately eastwards flow near 36°N of the (jet) frontal area around that gyre during cruise Amofront 1 (24 April to 26 May, 1994) (see also Prieur *et al.*, 1993; Claustre *et al.*, 1994).

Little is known about the causes for the "disappearances" of the two gyres. Perkins *et al.* (1990) reported a possible relation between unusual atmospheric forcing in the Gulf of Cadiz and a 9-day absence of the western gyre. Other mechanisms that may be important include the presence of a dynamically active subsurface layer (Heburn and La Violette, 1990), and considerable variations in transport through the Strait of Gibraltar caused by interaction between local wind stress and average atmospheric pressure over the western Mediterranean (Cheney and Doblar, 1982).

Recent foraminiferal distribution

The present-day planktonic foraminiferal assemblages in surface sediments from the Alboran Sea are strongly dominated by two species, *Globorotalia inflata* and *Globigerina bulloides*. This dominance can be traced along the Morocco–Algerian coast, where the Algerian Current dominates (Fig. 4). The Algerian current is a continuation of the

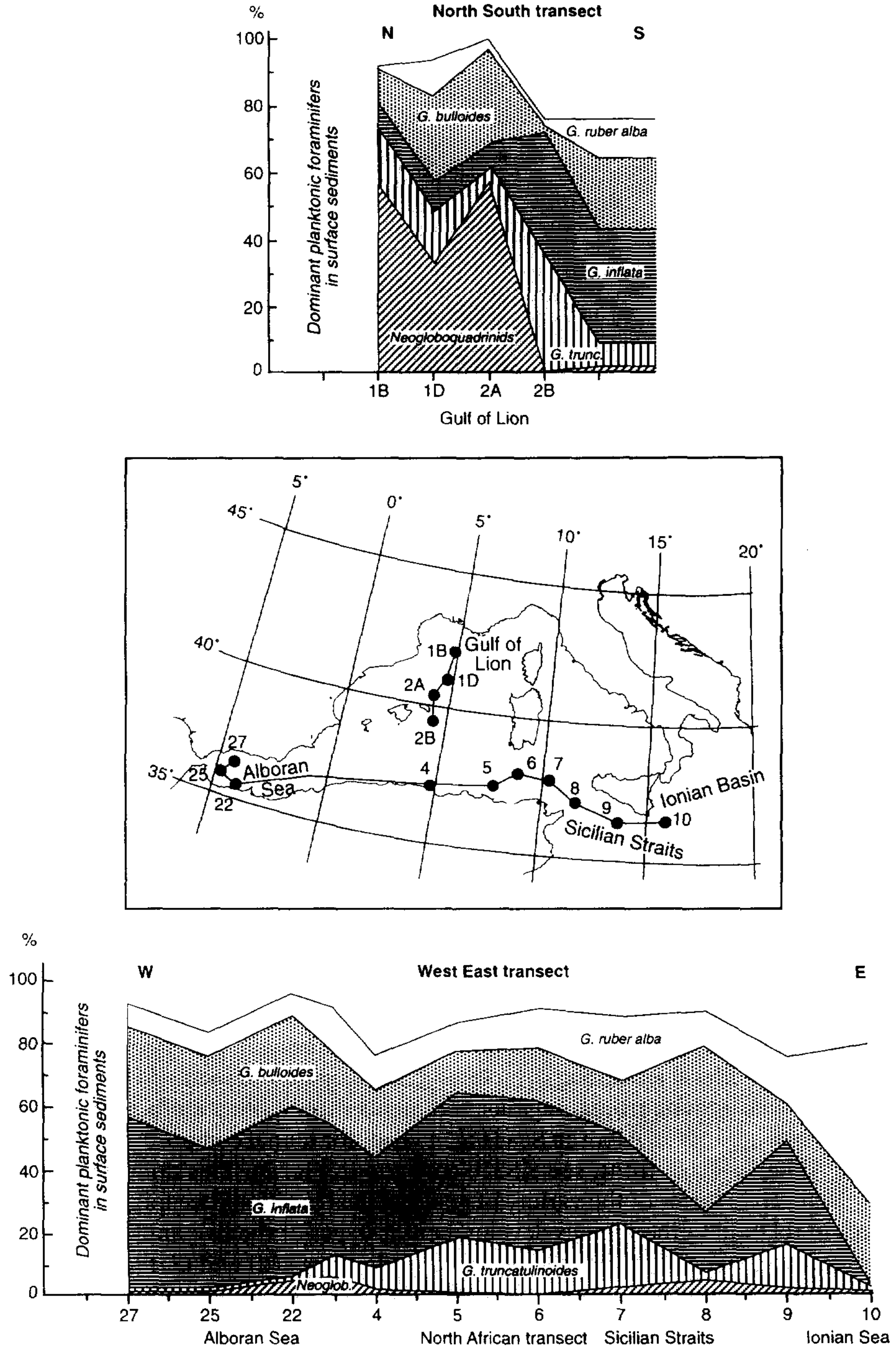

Fig. 4. Foraminiferal distribution (in percentages of total association) in surface sediments along the two indicated tracks.

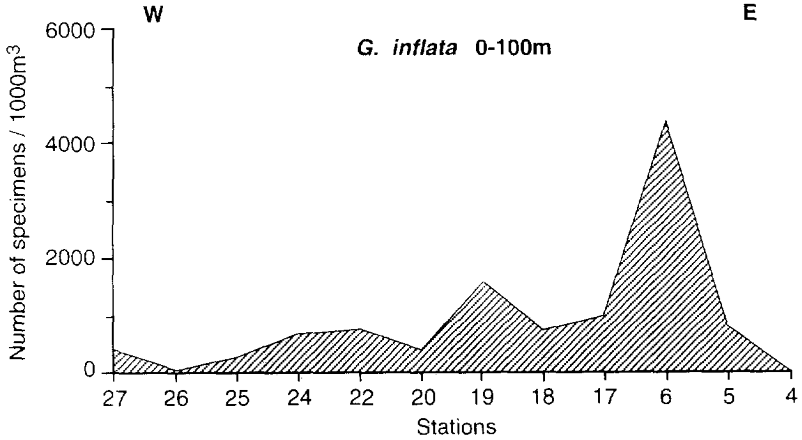

Fig. 5. Numbers of *G. inflata* in a lateral plankton tow across Alboran front. Track is indicated in Fig. 1. Note the very high peak abundance in Sta. 6, sampled immediately within the Almeria–Oran front, which was found slightly to the south and west of its more 'typical' position sketched in Fig. 1.

Atlantic inflow jet, which progresses eastwards as a series of more or less detached eddies (e.g. Millot, 1985; Arnone *et al.*, 1990; Perkins and Pistek, 1990).

In the Alboran Sea, dominant *G. bulloides* (50%) was found in early summer (June 1969) plankton tows, while *G. inflata* was found with percentages up to 14% (Cifelli, 1974). In November tows, Devaux (1985) found that *G. inflata* reached 57% of the planktonic foraminiferal assemblage, while *G. bulloides* was still present at 19%. In April 1990, *G. inflata* represented some 50% of the association and *G. bulloides* at least 20% (Pujol and Vergnaud-Grazzini, 1995). Summarizing, a dominance of *G. bulloides* prevails in late spring–early summer, whereas the rest of the year is characterized by a dominance of *G. inflata*.

A lateral towing transect across the Alboran Sea in April 1990 (Vicomed 3 expedition) demonstrated a general dominance of *G. inflata* (>30%, up to 90% in the front between Mediterranean and Atlantic waters). More specifically a very pronounced abundance-spike was found in Sta. 6 (Figs 1, 5), the location of which coincided with the Almeria–Oran front itself (identified by steep isopycnal slopes and in measurements of oxygen content and $\delta^{13}C$ values of surface waters). In this frontal zone, *G. inflata* contributes over 99% of the foraminiferal assemblage. Note that, although there seems to be a strong link between *G. inflata* and the frontal regions, sediments show quite a uniform abundance of this species throughout the Alboran Sea (Fig. 4; also, for faunal composition of sediments below the Almeria–Oran front, see KS310 core-top in Fig. 2). This uniform abundance should be viewed in terms of the variety of geographical positions occupied by the frontal structures in relation to the various developmental stages of the two anticyclonic gyres.

Combined dominance of *Neogloboquadrina pachyderma* (d) and *G. bulloides* is found in recent surface sediments of the Gulf of Lions (Fig. 4). In the Gulf of Lions, *N. pachyderma* dominates in (late) winter. In winter, strong cyclonic circulation causes shallowing of the density gradient (pycnocline) between surface waters and the Mediterranean Intermediate Water (MIW). This gradient, which is usually found at an average depth of about 200–250 m in the western Mediterranean (e.g. Perkins and Pistek, 1990),

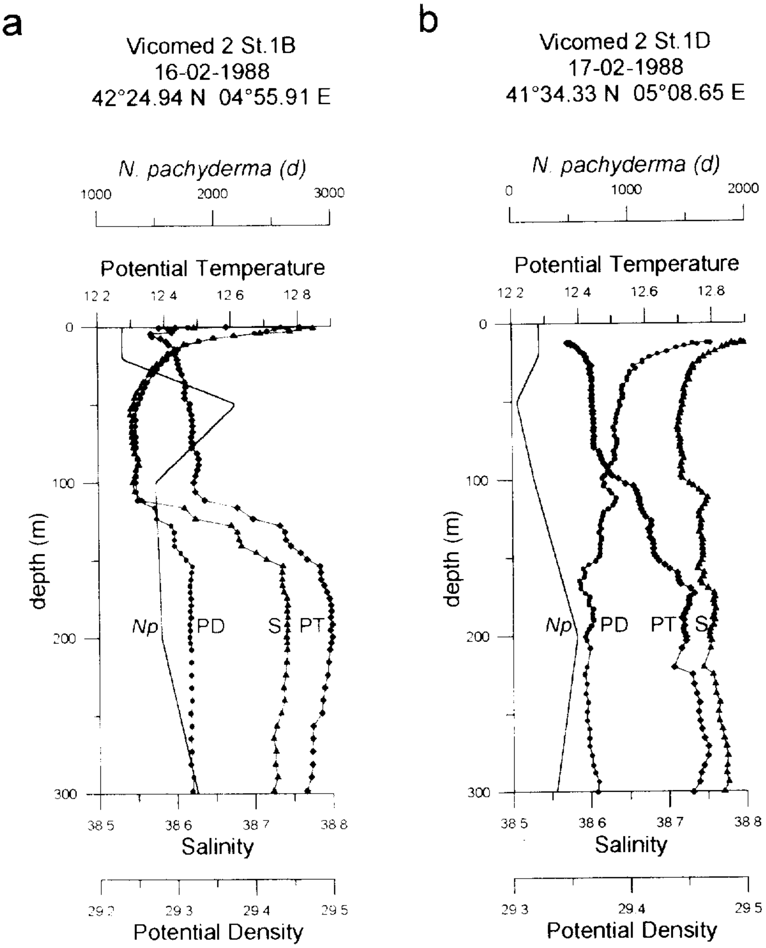

Fig. 6. (a) Potential Temperature (°C), Salinity (‰), Potential Density Anomaly (Potential Density—1000 kg m^{-3}), and numbers of *N. pachyderma* (dextrally coiled; numbers per 1000 m^3) in Vicomed 2 Sta. 1B. (b) As Fig. 6a, but for Vicomed 2 Sta. 1D. Note the different values on the *N. pachyderma* (d) abundance-axis, and the slightly different scale on the Potential Density Anomaly axis, as compared to Fig. 6a.

had shoaled to about 100 m at Sta. 1B of the Vicomed 2 expedition, which was visited on 16 February, 1988 (Fig. 6a). In addition, cooling of the surface layer had intensely weakened the density gradient, facilitating vertical (cross-isopycnal) mixing (Fig. 6a; $\sigma_\theta = 29.25$ kg m^{-3} at 50 m, and 29.32 kg m^{-3} at 200 m). Associated with the pycnocline, one commonly finds a distinct nutricline between nutrient-enriched MIW and oligotrophic surface waters (*cf* Minas, 1971). Substantial shoaling of the pycnocline (and nutricline), with at the same time a weakening of the pycnocline itself, would cause increased advection of nutrients into the euphotic layer where they can be used for phytoplankton production. As a result, a deep chlorophyll maximum (DCM) develops. As shown for Vicomed 2 Sta. 1B (Fig. 6a), *N. pachyderma* abundances in the water column are closely related to the shoaling (and weakening) of the pycnocline. Such a relation between shoaling of the pycnocline and associated nutricline, DCM formation, and *Neogloboquadrina* abundances has been reported also for other areas, by Fairbanks and Wiebe (1980), Fairbanks *et al.* (1982), Reynolds and Thunell (1986) and Reynolds Sautter and Thunell (1989). On theoretical grounds, it was suggested for the Mediterranean by Rohling and Gieskes (1989).

The profile of Vicomed 2 Sta. 1D (17 February, 1988; Fig. 6b) shows a distinct vertically homogenized salinity distribution. In addition, the temperature gradient (Fig. 6b) has become more irregular, and shows signs of admixture of cool surface waters to the core of MIW, lowering the temperatures between 200–400 m as compared to those found in nearby Sta. 1B (Fig. 6a). The profiles at Sta. 1D seem indicative of vertical mixing between MIW and surface waters, which is common in the Gulf of Lions in late winter (MEDOC Group, 1970; Stommel, 1972). The abundance pattern of *N. pachyderma* in Sta. 1D (Fig. 6b) is also very different from that in Sta. 1B (Fig. 6a). Not even a trace of peak abundances around 50 m is found. Instead, the abundances are minimal at that level. The presence of *N. pachyderma* in the rest of the water column may be remnant of earlier blooming in a DCM setting like that of Sta. 1B, before vertical mixing between MIW and surface water started.

The comparison of CTD profiles and *N. pachyderma* abundances in the Gulf of Lions, therefore, seems suggestive of a preferred habitat consisting of a shallow pycnocline. In such a configuration, nutrients from MIW become available at the base of the euphotic layer and a DCM develops.

The abundance of *G. bulloides* in the Gulf of Lions surface sediments can unfortunately not be understood with the available plankton tows of September 1986 (Vicomed 1) and February 1988 (Vicomed 2). Neither showed high numbers of *G. bulloides* in the watercolumn. It is anticipated that *G. bulloides* is abundant in late spring, as that is also its season of highest abundance in the Ligurian Sea (Vergnaud-Grazzini, 1973), around Sardinia (Cifelli, 1974), and in the Alboran Sea (Devaux, 1985). It seems that this opportunistic species may proliferate in whatever eutrophic setting. It is found widely distributed in the world ocean, with markedly increased abundances in upwelling areas (Kroon and Ganssen, 1989).

The faunal change at 8000 BP

Throughout the Alboran Sea, planktonic foraminiferal assemblages dominated by *N. pachyderma* with *G. bulloides* are replaced around 8000 BP by assemblages dominated by *G. inflata* with *G. bulloides*. This is true both in the percentages of the total assemblage, and in the numbers per gram dryweight (Figs 2, 3). According to the above described preferred habitats for *N. pachyderma* and *G. inflata*, this transition probably reflects a change from a generally shallow pycno-nutricline in the Alboran basin before 8000 BP, conducive to distinct DCM development with abundant *Neogloboquadrina*, to more or less modern conditions after that time. The modern conditions are dominated by a relatively deep position of the pycnocline between MIW and surface waters (about 200 m; a.o. Parilla *et al.*, 1986; Kinder and Parilla, 1987), while the surface layer contains an actively meandering jet of Atlantic inflow separated from Mediterranean waters by a distinct geostrophic front system, in which *G. inflata* proliferates.

The foraminiferal record reflects long-term average conditions, as illustrated by the discussed "averaging" in surface sediments of the faunal signature of today's (constantly migrating) frontal zones in the Alboran Sea. Therefore, the important faunal change

Table 1. Changes in transport through the Strait of Gibraltar caused by variations in sea level between −50 *and* +10 m *relative to the present. Values are calculated by varying sea level in the Bryden and Kinder* (1991) *hydraulic control model, with constant excess of evaporation over freshwater input* (*after Rohling and Bryden*, 1994)

Sea level (m)	Percentage of inflow
+10	105
+5	102
0	100
−5	98
−10	95
−15	93
−20	91
−25	88
−30	86
−35	84
−40	81
−45	79
−50	77

around 8000 BP should be explained with a change in the long-term average state of the basin.

The frontal zones, in which *G. inflata* proliferates, are related to the presence of the anticyclonic Alboran Sea gyres. The faunal change could, therefore, be addressed in terms of atmospheric forcing, which today seems to cause occasional disappearance of those gyres. The exact forcing condition, however, is still poorly defined and today appears to be the exception rather than the rule. This makes it impossible to evaluate whether such forcing may have dominated a configuration that was stable for more than 10,000 years prior to 8000 BP.

Instead, we suggest that the faunal change resulted from the rise of sea level since the last glacial maximum, which has been described in detail for the Atlantic Ocean from the study of fossil coral reefs off Barbados (Fairbanks, 1989). This glacio-eustatic sea level rise does classify as the type of long-term process required to explain the described faunal change around 8000 BP, and it would have influenced the Alboran Sea circulation by regulating the amount of water exchange through the narrow, shallow Strait of Gibraltar.

Around 8000 BP, sea level stood approximately 30 m lower than today (Fairbanks, 1989). Rohling and Bryden (1994) used the Bryden and Kinder (1991) hydraulic control model for the Strait of Gibraltar to calculate changes in the maximal exchange solution related to sea level change from −120 m to +10 m relative to the present, assuming that net evaporation over the Mediterranean remained constant at its present value (Table one, for sea level from +10 to −50). According to their study, maximal exchange with sea level at −30 m, and net evaporation equal to the present, is about 86% of its present value.

Between 8500 and 6500 BP, anoxic sediments have been deposited in the eastern Mediterranean, resulting (in part) from reduced net evaporation over the basin (Cita *et al.*, 1977; Vergnaud-Grazzini *et al.*, 1977; Williams *et al.*, 1978; Thunell *et al.*, 1987; Rohling and Gieskes, 1989). Therefore, the value of 86% determined for the exchange through the Strait of Gibraltar at 8000 BP, relative to the present, should be regarded as a maximum estimate. These arguments imply that more or less modern conditions with distinctly developed geostrophic fronts prevail in the Alboran Sea only when the volume of Atlantic inflow amounts to at least 86% of its present value. This should be confirmed with realistic models of the circulation through the Strait of Gibraltar and in the Alboran Sea.

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