Climatic and oceanographic changes for the last 25 cal ky bp in the Alboran Sea. A diatom inference

Cambios climáticos y oceanográficos durante los últimos 25.000 años en el Mar de Alborán inferidos a partir de diatomeas

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ABSTRACT

*The present work concerns the study of the Calypso piston core MD 95-2043 (36°09'N/2°37.269'W). In order to establish a stratigraphic time framework the age model is based on seventeen ^{14}C-dates, AMS radiocarbon ages measured on monospecific foraminiferal samples (*G. bulloides*). ^{14}C-dates were calibrated to calendar years in order to correct natural variations of ^{14}C. The CALIB 4.1 program was used for the calibration of ^{14}C-dates time record considered in this study that spans the last 26.5 cal ky BP. Average sedimentation rate for the time interval studied is 35.85 cm/ky.*

Based on the diatom record, paleoceanographic conditions favoured an increase in paleoproductivity during the Last Glacial Maximum (LGM) with a maxima occurred at ca. of Termination 1a (T1a), and during the Younger Dryas event (YD). During this period, meteorological conditions, with increased westerlies, would induce an intensified eastward flow which would displace the Western Anticyclonic Gyre (WAG) to the East. A possible displacement of the North Alboran upwelling system has also be considered. The major component of the diatom assemblage during the YD are the resting spores (RS) of Leptocylindrus danicus. The development of this species was probably favoured by the presence of the cooler and less saline Atlantic Surface Water (ASW) triggered by the diversions of meltwaters from the ice sheets surrounding the Atlantic.

The abundance of fresh-water diatoms was used as an aridity indicator, while opal phytoliths were linked to relatively wet conditions on land. During marine isotopic stage 2 (MIS2) until 14 cal ky BP the region supported a gradual climatic deterioration with a belt-grass loosing. Wind intensification was also deduced. During the Bølling-Allerød (B-A) climatic conditions would be warmer and moister. This conditions prevails until ca. 8 cal ky BP. When the re-establishment of vegetation belts and replenish of lakes were deduced. Nevertheless, during the YD climatic conditions could be dryer and windy.

RESUMEN

El presente trabajo enfoca el estudio del testigo de pistón tipo Calipso MD 95-2043 (36°09'N/2°37.269'W). La estratigrafía del testigo está basada en 17 edades de radiocarbono medidas sobre el foraminífero planctónico G. bulloides mediante la técnica AMS. Las edades de ^{14}C obtenidas fueron calibradas a edades de calendario para corregir las posibles variaciones naturales del ^{14}C. Para la calibración se empleo el programa CALIB 4.1, el resultado fue un periodo que comprendía los últimos 26.5 ka de calendario. La tasa de sedimentación media se estimó en 35.85 cm/ka para este periodo de tiempo.

El registro de diatomeas parece indicar que las condiciones paleoceanográficas del Mar de Alborán favorecieron el incremento de la paleoproductividad superficial durante el Ultimo Máximo Glacial (LGM), con máximos próximos a la Terminación 1a (T1a) y durante el Younger Dryas (YD). Durante el periodo comprendido en este estudio las condiciones metereológicas, con vientos del Oeste más intensos, inducirían a una intensificación del flujo de entrada hacia el Este desplazando al Giro Anticiclónico Occidental (WAG). Se especula un posible desplazamiento del sistema de surgencia localizado al Norte del Mar de Alborán hacia posiciones más orientales. El componente principal de la asociación de diatomeas durante el YD son las esporas de Leptocylindrus danicus. El desarrollo de esta especie pudo ser favorecido por la presencia de un Agua Superficial Atlántica (ASW) más fría y menos salina, este agua de características especiales pudo tener su origen en la fusión de las plataformas heladas que rodeaban el Atlántico.

La abundancia de diatomeas de agua dulce ha sido empleada como indicador de aridez, mientras que los fitolitos se han relacionado con condiciones húmedas en el continente. Durante el estadio isotópico marino 2 (MIS2) hasta 14 cal ka BP la región soportaba un deterioro climático gradual con pérdida del cinturón herbáceo. También se ha podido deducir una intensificación eólica. Durante el periodo Bølling-Allerød (B-A) las condiciones climáticas pudieron ser templadas y suaves. Estas condiciones prevalecieron hasta cerca de los 8 ka de calendario, se ha deducido el restablecimiento de los cinturones de vegetación y el relleno de los lagos. No obstante durante el YD las condiciones climáticas pudieron ser más frías y ventosas.

Key words: *diatoms, paleoproductivity, paleoclimatology, deglaciation, Late Pleistocene, Alboran Sea.*

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Introduction

The Mediterranean behaves as a system of *antiestuarine* circulation with surface water entering from the Atlantic and leaving the Mediterranean at depth (Bormans *et al.*, 1986). The circulation of the Alboran Sea is energetic, and is subject to strong seasonal variations related to fluctuations in the intensity of water exchange through the Strait of Gibraltar (Pistek *et al.*, 1985). The most streaking oceanographic features in the Alboran Sea are the Western Anticyclonic Gyre (WAG) and the Almeria-Oran density front (Fig. 1). Their shape, position and permanence depends of several factors such as thermohaline circulation, meteorological forcing, etc. (Parrilla and Kinder, 1987). Unlike most of the Mediterranean, the Alboran Sea has two systems of high biological productivity which are associated with WAG and the Almeria-Oran density front. To the northern limb of the WAG, an upwelling of subsurface waters occurs, and thus a frontal system develops along the eastern gyre (Fig. 1). Moreover, the present-day climatic system over the Mediterranean Sea is characterised by the establishment of a very stable high-pressure system, related to the Intertropical Convergence Zone (ITCZ) (Cramp and O'Sullivan, 1999). Its position is critical in determining climatic and oceanographic patterns in the Alboran Sea (Parrilla and Kinder, 1987).

Variations in paleoproductivity related to variations in climatic and paleoceanographic conditions has been widely studied in the area (Abrantes, 1988; Caralp, 1988; Weaver and Pujol, 1988; Turon and Londeix, 1988; Vergnaud-Grazzini and Pierre, 1991; Targarona *et al.*, 1997; Sierro *et al.*, 1998, Bárcena and Abrantes (1998), Cacho *et al.*, (in press), and Bárcena *et al.* (submitted).

Recent SST studies on core MD95-2043 (Cacho *et al.*, in press), Bárcena *et al.*, submitted) show evidence of a clear connection between the Greenland $\delta^{18}O$ record in GISP2 and its Dansgaard-Oeschger (D-O) events (Meese *et al.*, 1997) and Alboran's SST, as well as a good coherence among the temperature minima in both records. The influence of the Heinrich events in the Alboran Sea with important invasions of polar waters into the Alboran sea have been documented by the presence of a peak in the foraminifer *Neogloboquadrina pachyderna* (s) sinistral (Cacho *et al.*, in press; and Bárcena *et al.*, submitted).

Northern Hemisphere climate is clearly linked to that of high-latitude ice sheets, with glacial aridity and interglacial humidity (Sarnthein *et al.*, 1982; Stabell, 1986). During glacials the ITCZ migrates to the south (Sarnthein *et al.*, 1982) favouring the location of a low-pressure system over the Mediterranean and prevailing westerlies, and therefore favouring "red-rain" over the Mediterranean (Parrilla and Kinder, 1987). Previous studies by Bárcena *et al.* (1997), Flores *et al.* (submitted), and Bárcena *et al.* (submitted), have shown the different behaviours between two types of siliceous wind-transported microfossils, freshwater diatoms and opal phytoliths. The abundance of fresh-water diatoms was used as an aridity indicator, while opal phytoliths were linked to relatively wet conditions on land.

The present work is aimed at the understanding of the climatic and paleoceanographic changes during the last deglaciation, with previous observation from marine isotopic stage 2 (MIS2) and the Last Glacial Maximum (LGM) to present day, in the Alboran Sea. Regional atmospheric patterns would induce paleoceanographic and paleoproductivity changes displacing the Alboran's high fertility systems eastward. Besides, Northern Hemisphere climatic and oceanographic changes would also affect the Alboran Sea introducing fresh waters through the Strait of Gibraltar. Climatic changes in North Africa as well as wind regime have been also study base in continental microfossils.

Materials and methods

The present work concerns the study of a calypso piston core MD 95-2043 was taken during the 1995 IMAGES cruise at 36°09'N/2°37.`W and 1841 m water depth.

Micropaleontological studies were carried out on samples spaced at 10 cm intervals in core MD 95-2043. Samples were prepared according to the method outlined in Bárcena and Abrantes (1998). Magnification was x1000, and the recommendations of Schrader and Gersonde (1978) were used as a basis for diatom valves counting. For evaluation of the state of preservation of diatom valves we followed the recommendations of Bárcena and Flores (1991).

Results

In order to establish an stratigraphic framework, constant sedimentation rates were assumed between the age control points, and linear interpolation was used to obtain ages between the control points. The age model is based on seventeen ^{14}C-dates, AMS radiocarbon ages measured on monospecific foraminiferal samples, it has been widely described in Cacho *et al.* (in press). To correct natural variations and improve time resolution ^{14}C-dates were calibrated to calendar years using the CALIB 4.1 (Stuiver and Reimer, 1993). The approximate time recorded in the core is 26.5 cal ky. Resulting sedimentation rate have an average value of 35.85 cm/ky for the studied time interval.

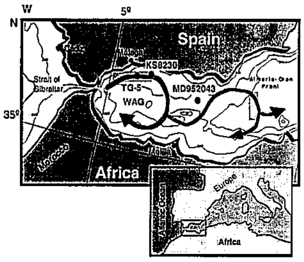

Figure 1- Studied area. Position of the studied core in this paper as well as the site cores TG-5 and KS8230. Location of the predominant oceanographic features of the Alboran Sea, the western anticyclonic gyre (WAG) and the Almeria-Oran Front. Shadow zones represent today's' high fertility areas.

Figura 1- Area de estudio. Localización del testigo estudiado en este trabajo así como la posición de los testigos TG-5 y KS8230. Localización de los patrones ocanográficos mas importantes del Mar de Alborán, el giro anticiclónico occidental (WAG) y el frente Almería-Orán. Las zonas sombreadas representan las zonas actuales de alta fertilidad.

The range of the variations in diatom number fluctuates from an absence of diatom valves to abundance of 3,9 x10^{6} valves/gr of dry sediment (Fig. 2). In the Alboran basin abundances are lower than normally observed in strong upwelling areas where the number of diatom valves in the sediments may reach millions. During marine isotopic stage 2 (MIS2) diatoms are present, the occurrence of several peaks from MIS2/MIS3 boundary to Termination 1a (T1a) has been observed. During the deglaciation diatom abundance shows strong fluctuations. The Bølling-Allerød period (B-A), which spans about 2000 years, appears characterised by an important reduction in diatom numbers. Following the B-A, related to the YD, diatoms reach the highest abundance. The diatom assemblage found at this peak in core MD95-2043 is dominated by resting spores of *Leptocylindrus danicus* (63 to 89 %). The second major component of the assemblage is *Paralia sulcata* (4 to 16 %). T1b is marked by a continuous and rapid decrease in diatom abundance with a final disappearance of diatoms in the early Holocene, very few samples contained entire diatom valves, mostly only fragments could be found. At the surface, diatoms reappear, but in contents lower than the values found downcore for MIS2 and the Termination (Fig. 2).

Freshwater diatoms together with phytoliths were counted along core MD95-2043 (Fig. 2). The main fresh-water diatom in the Alboran Sea is *Aulacoseira* sp, a planktonic and lacustrine diatom, together with other limnobiontic forms (*Cyclotella ocellata* and *Stephanodiscus astrea*). Abundance pattern of this groups is parallel to the total diatom assemblage. Maximum abundance of both groups occurs during the LGM and the YD. The group disappears after 8.5 ky BP, reappearing in the surface samples. Fresh-water diatoms and phytoliths, show clear differences. During the MIS2 until T1a, fresh-water diatoms have a relatively high abundance with a decreasing tendency towards T1a. During the B-A period, the group has a very low abundance. For the YD period the fresh-water group presents a peak of higher abundance and afterwards follows a decreasing tendency. The phytoliths pattern is the opposite of the previously observed fresh-water diatoms, they reach their highest value during the deglaciation, after the YD event, moreover in the MIS2 the appearance of the group is constant trough time (Fig. 2).

Discussion and conclusions

Current-hydrography reveals the existence of two high productivity systems in the Alboran Sea, the WAG and the Almeria-Oran Front (Fig. 1). Previous studies by Abrantes (1988), Bárcena and Abrantes (1998) and Bárcena *et al.* (submitted) have already related diatom presence in Alboran Sea sediments to upwelling conditions in the overlaying waters. Therefore, the high abundance of diatoms in the sediment are related to the productivity of the surface waters, and the variations in downcore diatom abundance is the result of changes in paleoproductivity.

The persistence of the double gyre of the Alboran Sea is variable and its permanence depends of several factors (thermohaline circulation, meteorological factors, etc.) (Parrilla and Kinder, 1987). The present-day Mediterranean climate type is due to the position of the ITCZ in the upper atmosphere, its seasonal migration, and the influence that the ITCZ has upon more localised pressure systems. During glacial period the ITCZ migrates to the south favouring the localisation of a low-pressure system over the Mediterranean and prevailing westerlies (COHMAP Members, 1988), its dominance induces maximum stream flux, the stream enter directly till the centre of the basin, and the WAG is displaced to the east (Parrilla, 1984). Vergnaud-Grazzini and Pierre (1991) suggested that before 16 ky, prevailing westerlies and low pressures over the Mediterranean favoured the eastward displacement of the WAG of the Alboran Basin.

Recent studies by Bárcena *et al.* (submitted) on two cores located at the continental shelf (Fig. 1), core KS8230 (36°27'N/3°53'W, and 795 m water depth), and core TG-5 (36°23'N/4°15'W, and 626 m water depth) show a clear evidence of reduced surface paleoproductivity for the time period studied in this work by comparing with surface paleoproductivity recorded in core MD95-2043 (Fig. 3). Both cores are located under the influence of today's upwelling system at the northern limb of the WAG. In overview, one can asses that for the all time interval considered in this study, highest productivity was displaced towards the East; core MD95-2043 record maxima diatom abundance, while TG-5 and KS8230 record the lowest values in paleoproductivity. Therefore, we infer that during MIS2 meteorological conditions would induce an intensified eastward flow which would displaced the WAG to the East, and the North Alboran upwelling system would be moved, therefore maxima fertility in surficial waters could occurs in the eastern area.

Based on the diatom record paleoceanographic conditions favours increases in paleoproductivity from 22,5 ky to 16 ky during the LGM with a maximum at ca. T1a. During the B-A event a significant reduction in paleoproductivity was observed, but a new increase in paleoproductivity occurs during the YD (Fig. 2). Several other paleoproductivity indicators point to changes in paleoproductivity during the last 25 ky in the Alboran Sea that have been attributed to variations in the oceanographic conditions by several authors (Abrantes, 1988; Weaver and Pujol, 1988; Turon and Londeix, 1988; Targarona *et al.*, 1997; Vergnaud-Grazzini and Pierre, 1991). During the Holocene inferred paleoproductivity decreased to the lowest values of the last 23 ky; paleoproductivity was slightly reestablished recently (Fig. 2).

Recent SST studies on core MD95-2043 (Cacho *et al.*, in press) show evidence of a clear connection between the Greenland $\delta^{18}O$ record in GISP2 (Meese *et al.*, 1997) and its D-O events and Alboran's SST, as well as a good coherence among the temperature minima in both records. Cacho's study also recognise the influence of the Heinrich events in the Alboran Sea, and assess that important invasions of polar waters occurred in base to the presence of *N. pachyderma* (s) (Cacho *et al.*, in press). In this sense, diatom assemblages respond to these cool water invasions. The increase in paleoproductivity during the YD

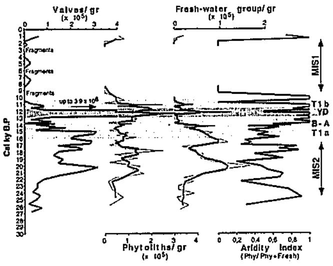

Figure 2- Absolute abundance of diatom valves, freshwater diatoms and opal phytoliths per gram of dry sediment on core MD95-2043. Thicker line indicates a three-point smoothing. The aridity index has been calculated as the resulting of the following equation: phytoliths/ phytoliths+freshwater diatoms. Ages are given in calendar ky BP after calibration with CALIB 4.1 program. Grey bar marks the deglaciation interval, darkest bar indicates the Younger Dryas event (YD). T1a: Termination 1a; B-A: Bølling-Allerød period; T1b: Termination 1b.

Figura 2- Abundancia absoluta de valvas de diatomeas, diatomeas de agua dulce y fitolitos por gramo de sedimento seco en el testigo MD95-2043. Las líneas gruesas indican un suavizado de tres puntos. El índice de aridez se ha calculado con la siguiente fórmula: fitolitos/ fitolitos+diatomeas de agua dulce. Las edades se expresan en edades de calendario y se han calibrado con el programa CALIB 4.1. La barra gris marca el intervalo de la deglaciación, la gris oscura indica el YD. T1a: Terminación 1a; B-A: perido Bølling-Allerød; T1b: Terminación 1b.

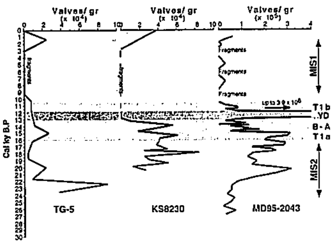

Figure 3- Diatom valves per gram of dry sediment for core TG-5, KS8230 and MD95-2043.

Figura 3- Valvas de diatomeas por gramo de sedimento seco para los testigos TG-5, KS8230 y MD95-2043 was inferred from to the peaks in *L. danicus* RS and *P. sulcata*. *L. danicus* is a common neritic species world-wide distributed associated to cold and temperate waters, this species has been related to ASW which induces stability in the upper part of the water column (Delgado, 1990), it was also recorded in lenses of low salinity waters (Estrada, per. com). The YD is the last of a long series of alternations between colder and warmer conditions occurred during the Last Glacial Period, the D-O events (Broecker, 1992). As proposed by Broecker (1992), the YD cold event was triggered by the diversions of meltwaters from the ice sheets surrounding the Atlantic which spread fresh water across the North Atlantic and therefore Mediterranean circulation patterns would be also affected by this. Therefore, a salinity decrease in the incoming ASW into the Alboran Sea would explain the *L. danicus* peak in core MD95-2043, as resulting from relatively cooler and low salinity waters and stratification in the upper part of the water column.

The fresh-water diatom group and opal phytoliths are common in surface sediment samples from the Alboran Sea (Bárcena *et al.*, submitted). Opal phytoliths, particles growing within vascular plants, are injected into the atmosphere during dry-season brush fires. Fresh-water diatoms (*Aulacoseira* sp) come from the deflation of diatomaceous deposits in dry lake beds. Hence, the presence of a mixture of microfossils with distinct ecological requirements, terrestrial and lacustrine environments, allow us to interpret this fact as a wind transported assemblage more than a run-off origin. Dust storms are common in North Africa during the arid and dry seasons, and the presence of "red rain" over the Spanish coast has been widely described. This "red rain" is related to south-westerlies generated by low pressures on the Gulf of Cadiz (Parrilla and Kinder, 1987). African climate is clearly linked to that of high-latitude ice sheets, with glacial aridity and interglacial humidity (Sarnthein *et al.*, 1982; Stabell, 1986). Besides, during glacial periods the ITCZ migrates to the south favouring the localisation of a low-pressure system over the Mediterranean and prevailing westerlies, and therefore favouring "red-rain" over the Mediterranean. The abundance of fresh-water diatoms was used as an aridity indicator, while opal phytoliths were linked to relatively wet conditions on land. Also, fresh-water diatoms would indicate arid conditions in North Africa with lake desiccation during the MIS2 until 15 cal ky BP, the progressive phytoliths decline would also indicate a gradual climatic deterioration and a gradual belt-grass loosing with a wetter episode from 19 to 17 cal ky BP (Fig. 2). LGM would be characterised by an intensification of the winds while the B-A would correspond to the re-establishment of vegetation belts and replenish of lakes which continues throughout the rest of the deglaciation and prevails until ca. 8 cal ky BP (Fig. 2). Therefore, climatic conditions would be warmer and moister. Nevertheless, during the YD climatic conditions could have been relatively dryer, as indicated by the presence of fresh-water diatoms and the reduction in opal phytoliths. However, the total windblown particles was high during this interval which could indicate a wind intensification. Besides an aridity index has been calculated as the resulting of the following equation: phytoliths/phytoliths+freshwater diatoms. The index indicates the same dry and wet episodes that those described before (Fig. 2).

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