

## 10. INITIAL DIATOM RECORD OF SITES 657 AND 658: ON THE HISTORY OF UPWELLING AND CONTINENTAL ARIDITY<sup>1</sup>

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### ABSTRACT

Detailed analyses of samples recovered from the high-resolution Quaternary section cored at Ocean Drilling Program Site 658 reveal that very high abundances ( $6.4-8.3 \times 10^7$  valves/g dry sediment) of marine diatoms occur in interglacial oxygen isotope stages 7.5 and 9.3. Smaller abundance peaks ( $29-300 \times 10^5$  valves/g dry sediment) are present near oxygen isotope stage boundaries 1/2, 5/6, 9/10, 11/12, and 13/14. Therefore, high abundances of diatoms, interpreted as high productivity, are related to terminations.

The Quaternary freshwater diatoms have their highest abundances mainly in sediments deposited during interglacial periods, but they are also recorded during glacial intervals (oxygen isotope stages 2 and 8), and near terminations (stage boundaries 7/8 and 15/16).

The Pliocene freshwater diatom record indicates a frequency decrease at 2.8 Ma. It is suggested that the freshwater diatom frequency decrease indicates either a change to a more humid climate (assuming eolian transport) or a change to a more arid climate (assuming fluvial transport).

### INTRODUCTION

This paper deals with the diatom record of Ocean Drilling Program (ODP) Sites 657 and 658 on the northwestern African margin. The marine sediment record has been examined to unravel the paleo-productivity history of the upwelling region off the shore of Cap Blanc. Moreover, the freshwater diatom occurrence has been quantified to reconstruct the history of atmospheric circulation and climate on the African continent.

In general, the changes in climates of Africa were clearly linked to those of high-latitude ice sheets, with glacial aridity and an interglacial humidity. The underlying fluctuations in trade-wind intensity also governed circulation and upwelling changes.

While Site 657 is situated clearly outside the influence of coastal upwelling, Site 658 lies directly below one of the major nearshore cells of present-day oceanic upwelling in the world oceans (Fig. 1). Sediments deposited at these sites contain eolian dust records dominated by the input from the zonal flow of the Saharan Air Layer (African Easterly Jet). In addition, Site 658 is strongly influenced by the dust supply from the meridional trade winds (Ruddiman, Sarnthein, et al., 1988).

Fluctuations in marine diatom abundance may provide an indication of past changes in surface productivity (i.e., changes in upwelling intensity). It should be noted that two different methods have been used in the low-latitude Atlantic to infer surface productivity from diatom abundances. There is a problem in the approach using abundances in that the siliceous cell walls of diatoms are preserved in areas of both high productivity and low silica dissolution. Normally, diatoms dissolve due to undersaturation of pore- and seawater with respect to opal. It is possible, therefore, that fluctuations in abundance are related to differential silica dissolution, so that diatom maxima are related to low dissolution and diatom minima to high dissolution. Stabell (1986b), Pokras (1987a), and Pokras and Molino (1986), however, found that primary

productivity mainly controls the abundance of diatoms in the sediments, maybe directly, maybe indirectly, via a control of the silica saturation level of the pore water.

Fluctuations in the abundance of freshwater diatoms found in the sediments of the eastern equatorial Atlantic may, or most likely do, reflect climatic changes on the adjacent African continent. Freshwater diatom abundance maxima may reflect phases of enhanced deflation and wind transport during dry episodes (Parmenter and Folger, 1974), but they may also be indicative of increased riverine input, which is correlated with humid episodes on the continent (discussion in Gasse et al., in press).

### MATERIALS AND METHODS

Site 657 is situated at  $21^{\circ}19.89'N$  and  $20^{\circ}56.93'W$  at a water depth of 4222 m on the lower continental rise 380 km west of Cap Blanc. Two holes were cored. Diatom samples were analyzed only in the upper seven cores (60 mbsf) of Hole 657A, since samples from Cores 108-657A-5H through -18X were barren of diatoms (Ruddiman, Sarnthein, et al., 1988). The oldest diatom sample analyzed from this site is from a depth of about 35 mbsf and has an estimated age of 0.91 Ma (Ruddiman, Sarnthein, et al., 1988).

Site 658 is situated at  $20^{\circ}44.95'N$  and  $18^{\circ}34.85'W$  at a water depth of 2263 m on the continental slope 160 km west of Cap Blanc. Three holes were cored: 658A, 658B, and 658C. The oldest sediments, with an estimated age of 3.5-3.8 Ma, were reached in Hole 658A at a sub-bottom depth of 300 m (Ruddiman, Sarnthein, et al., 1988). Diatom samples were taken from all cores in Hole 658A and from Cores 108-658B-2H and -3H. Depth, stratigraphy, and time correlation of Holes 658A and 658B were established by means of magnetic susceptibility and oxygen and carbon isotope records. The composite depth values of both sections were taken from Ruddiman, Sarnthein, et al. (1988) and Sarnthein and Tiedemann (this volume).

Diatom samples were prepared according to the procedure described in Kaland and Stabell (1981), adding Dynospheres as a marker for absolute control in quantitative estimates. About 0.02 g dry sediment was oxidized in  $H_2O_2$  and repeatedly washed. Calcareous matter was removed with HCl. Dynospheres, monosized polymer particles, were added as the last step. For 0.02 g dry sediment, about  $1.5 \times 10^5$  Dynospheres were added. With this method only the weight of the sediment sample and the number of Dynospheres added need to be known; the number of diatom valves/g dry sediment can then be calculated.

At least two traverses (75 fields of view) of each slide were counted at  $40\times$  magnification, and the analyzed number of traverses was

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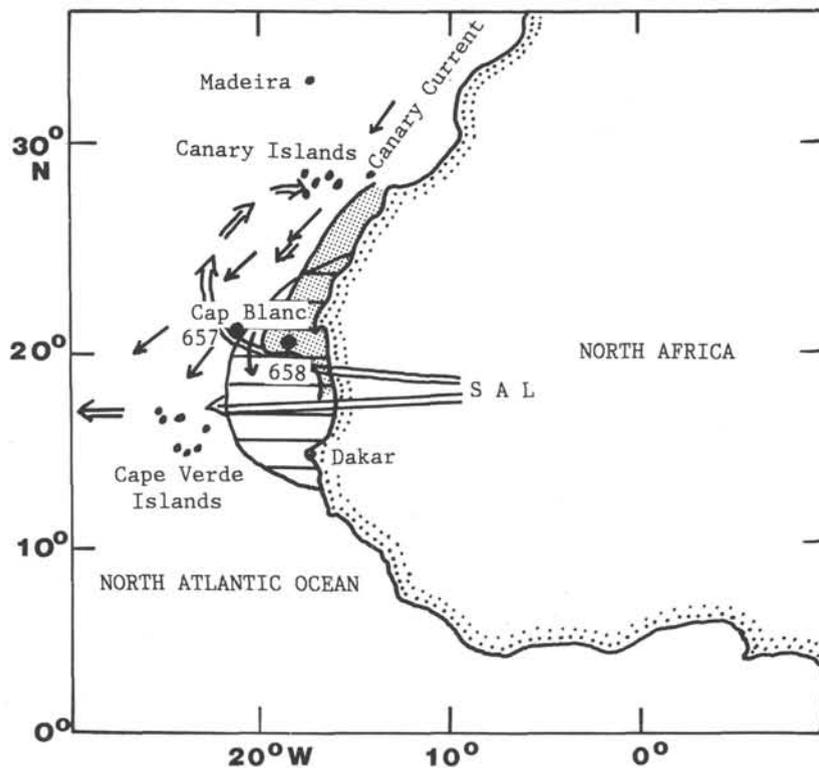


Figure 1. Site location map (redrawn from Ruddiman, Sarnthein, et al., 1988) showing ocean currents (filled arrows); upwelling cell (stippled area); atmospheric haze, northern summer (dashed area); and wind pattern (open arrows).

increased with decreasing diatom abundance. I correlated the abundance of diatom valves with surface productivity, as did Stabell (1986b), because diatoms occur in particularly high numbers in high surface productivity areas. Pokras (1987a) used factor analysis of the species composition to infer diatom productivity.

In the present investigation, the number of diatom valves/g dry sediment varied from 0 to about  $9 \times 10^7$ . For marine diatoms, low abundance is defined as  $\leq 0.5 \times 10^7$  diatom valves/g dry sediment; medium abundance, as  $0.5\text{--}1.2 \times 10^7$  diatom valves/g dry sediment; and high abundance, as  $\geq 1.2 \times 10^7$  diatom valves/g dry sediment. For freshwater diatoms, high abundance is defined as  $\geq 1 \times 10^5$  valves/g dry sediment. Abundances are based on total sediment; fluctuations in carbonate content will therefore affect the distribution pattern. However, as shown in Stabell (1986b), even with large fluctuations in calcium carbonate percentages with time, the general pattern in diatom abundance based on total sediment does not differ significantly from that on a carbonate-free basis.

Diatom data are presented as absolute numbers of diatom valves vs. core depth and time. The chronology for Site 658 is deduced from detailed oxygen isotope records of *Cibicides wuellerstorfi* (Sarnthein and Tiedemann, this volume), assuming a constant sedimentation rate between the midpoints of stages as defined by the SPECMAP group (Imbrie et al., 1984; Martinson et al., 1987). For the upper 100 m at Site 658, an attempt was made to analyze at least one sample from every core section ( $\geq 1.5$  m between samples). However, sampling gaps occur between 14.88 and 22.15 mbsf (only one sample at 17.87 mbsf), 30.06 and 32.15 mbsf, 56.59 and 60.65 mbsf, 76.98 and 79.15 mbsf, and 86.70 and 89.35 mbsf. There is a hiatus of 24.26 k.y. between 8.83 and 9.10 mbsf. The sampling intervals are, on the average,  $< 5$  k.y. between sampling gaps, except at the interval from 9.70 to 14.88 mbsf. Sedimentation rates range between 9.2 cm/k.y. (152–183 ka) and 26.0 cm/k.y. (215–225 ka). Between 100 and 300 mbsf at Site 658, the sampling density was much coarser, averaging 3 samples/core. There is a sampling gap of 15 m between 170 and 180 mbsf. The changes in the sedimentation rate are not large enough to explain the fluctuations in the absolute number of diatom valves.

Only two taxa, *Thalassionema nitzschioides* Grunow and *T. nitzschioides* var. *parva* Heiden, are presented on the subgeneric level in this paper. They are expected to provide further insights into the changes in river runoff and upwelling intensity. *Thalassionema nitzschioides* sensu stricto has a cosmopolitan distribution and is confined primarily to neritic areas (Smayda, 1958). Within its cosmopolitan distribution, several thermal clones can be distinguished.

*Thalassionema nitzschioides* is long and narrow, with a length-to-width ratio of up to 17. Most specimens found in the sediments are broken. Each apical end was counted as 1/2, so that two ends are equal to one frustule. Central pieces were not counted. *Thalassionema nitzschioides* var. *parva* was distinguished on the basis of its small size and its smaller length-to-width ratio of about 3.

The other taxa encountered were grouped together in oceanic (holoplanktic), neritic (meroplanktic), and freshwater species. Resting spores were counted separately and were not included in the total marine diatom calculations. High numbers of resting spores are generally interpreted as indicating high coastal productivity and upwelling (Sancetta, 1982).

## RESULTS

### Site 657

Diatoms were only found in the upper 35 m of section at this site (Fig. 2). The pelagic sediments at this site are broken by a slumped sediment mass derived from a high productivity upwelling area on the continental slope, which occurs between 13.6 and 26.2 mbsf and is assumed to be of Pleistocene (lowermost Brunhes) age (Ruddiman, Sarnthein, et al., 1988). A peak in the abundance of marine diatoms and their resting spores is present at about 20 mbsf. Oceanic and neritic species occur in about the same numbers at this depth and total about  $20 \times 10^5$  valves/g dry sediment. Resting spores are present with about  $11 \times 10^5$  spores/g dry sediment.

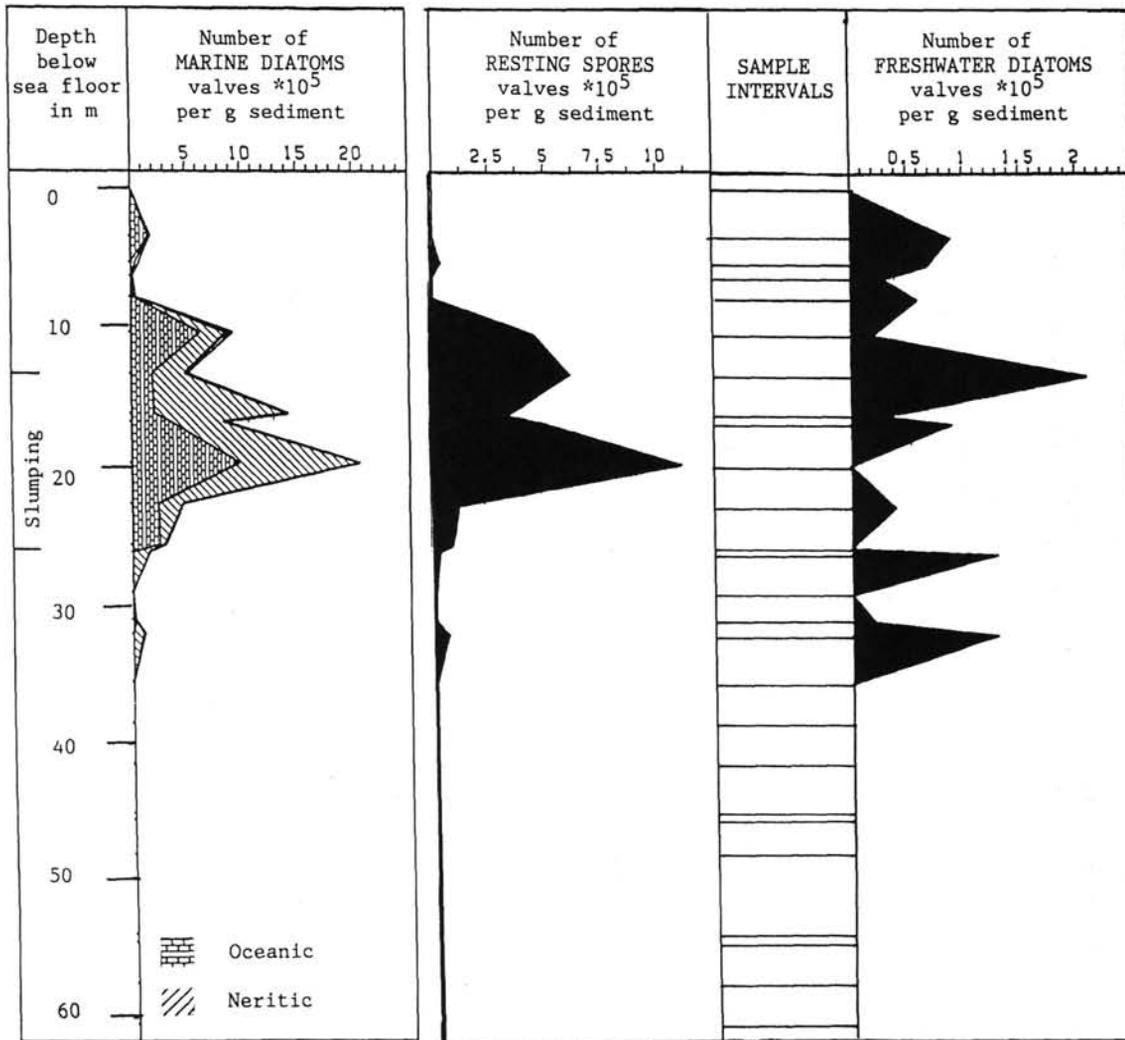


Figure 2. Downcore diatom distribution at Site 657.

The abundance of marine diatoms and their resting spores decreases above 20 mbsf with only minor observed occurrences above 10 mbsf. *Thalassionema nitzschioides* and its variety *parva* only occur as traces throughout the analyzed interval. The marine diatoms are concentrated therefore in the slumped sediments, but they extend a few meters into the pelagic sediments above and below. Freshwater diatom abundance alternates downcore, with abundance maxima at 3.5, 13.7, 26.3, and 32.7 mbsf. Values range from 1 to  $2 \times 10^5$  valves/g dry sediment (Fig. 2). Note that freshwater diatoms also occur above and below the slumped sediments.

#### Site 658

The upper 100 m of sediment from Site 658 has been analyzed in detail, whereas the interval from 100 to 300 mbsf was only coarsely sampled. Figure 3 shows the distribution of marine diatoms and their resting spores together with the distribution of freshwater diatoms vs. depth. The analyzed interval falls into four parts.

1. From 290 to 220 mbsf, there is a very low abundance of marine diatoms and their resting spores, and freshwater diatoms occur in the majority of the samples.

2. From 220 to 205 mbsf, there is a high abundance of marine diatoms, and freshwater diatom distribution is similar to (1) above.

3. From 205 to 100 mbsf, there is a fairly high abundance of marine diatoms, but freshwater diatoms only occur in a few samples.

4. From 100 to 0 mbsf, there are large fluctuations in marine and freshwater diatom abundances (discussed in detail below).

Diatom distribution in the upper 100 m (part 4 above of Fig. 3) is shown in Figure 4. The general abundance pattern for marine species (Fig. 4) shows a medium amount of marine diatoms ( $50\text{--}120 \times 10^5$  valves/g dry sediment) from 100 to about 50 mbsf. Between 50 and 33 mbsf, there are two high abundance maxima with the total number of valves at 643 and  $831 \times 10^5$  valves/g dry sediment, respectively. The upper 30 m of the section are characterized by low abundances ( $<50 \times 10^5$  valves/g dry sediment). Based on the abundance pattern for marine diatoms, therefore, the analyzed part of the core can be divided into three abundance zones.

These abundance zones may reflect sampling intervals. Assemblage Zone I (AZ I) has a low sampling density, although there is the possibility that denser samples would give abundance patterns similar to Assemblage Zones II and III (AZ II and AZ III). Extreme abundance maxima, such as those which characterize AZ II, may also have been missed in oxygen isotope stages 11 and 15, where sampling gaps are present.

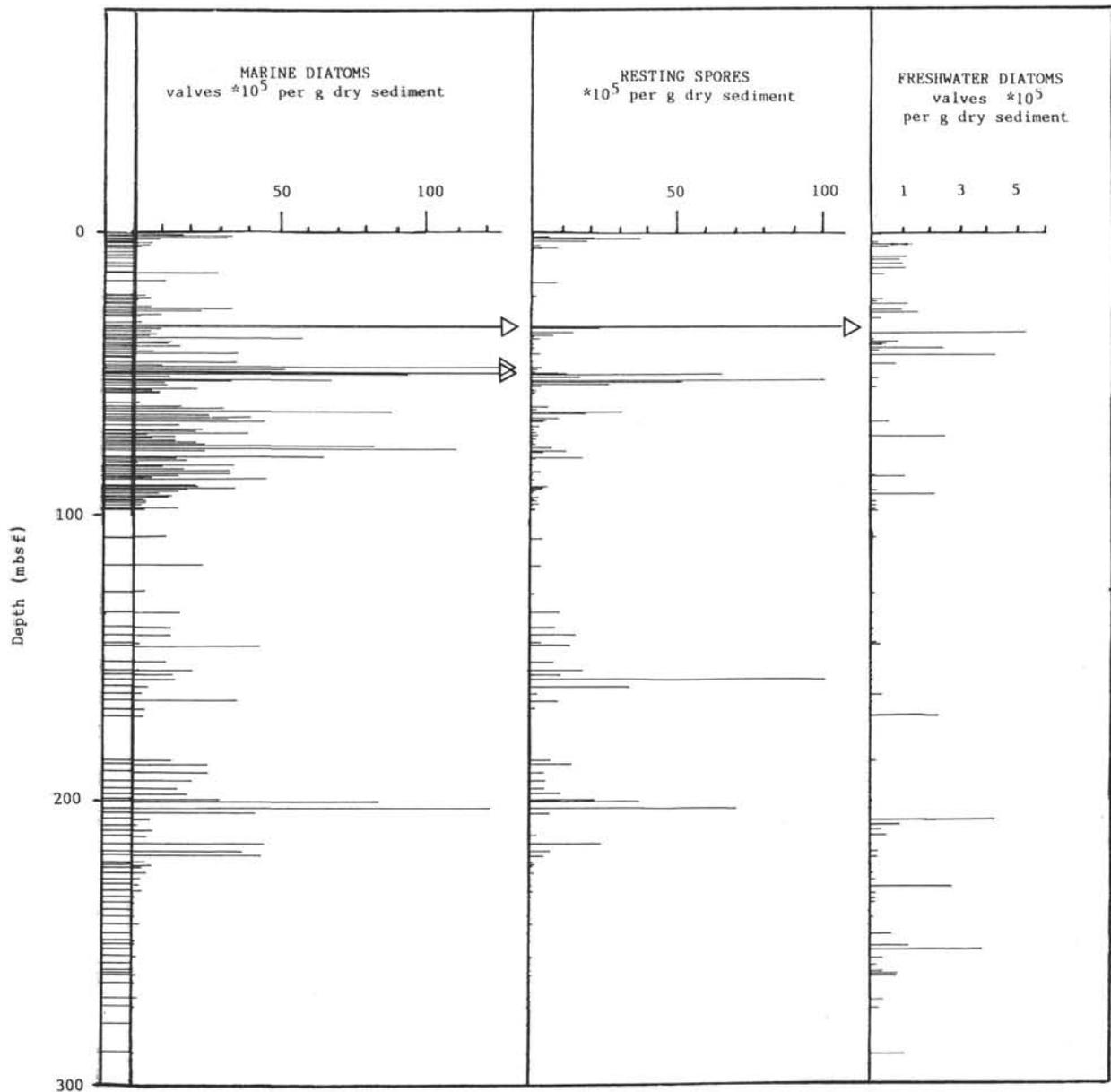


Figure 3. Downcore diatom distribution at Site 658.

#### Assemblage Zone I (0–33 mbsf)

This zone has three small abundance peaks of  $29\text{--}35 \times 10^5$  valves/g dry sediment at 1.9, 14.9, and 27.1 mbsf, and oxygen isotope stages 1/2, 5.4, and 7.3, respectively. The resting spores increase just prior to the two upper abundance peaks. The number of *T. nitzschioides* increases very slightly at 27.1 mbsf but not at the peaks above, whereas *T. nitzschioides* var. *parva* shows very slight increases at both 27.1 and 1.9 mbsf (not evident in Fig. 4).

#### Assemblage Zone II (33–50 mbsf)

Two extreme abundance maxima occur at about 33 and 47–50 mbsf, with their maxima at oxygen isotope stages 7.5 and 9.3, respectively. The maximum at about 33 mbsf covers two samples 50 cm apart, while the one at 47–50 mbsf covers six samples and is divided into two separate peaks. At both maxima, which are dominated by oceanic species, resting

spores start to increase prior to their increases in general abundance. *Thalassionema nitzschioides* has a very high abundance only at 33 mbsf, while *T. nitzschioides* var. *parva* has very high abundances at both maxima.

Between the two maxima, there are three small to medium abundance peaks of  $36\text{--}60 \times 10^5$  valves/g dry sediment at 37.7, 43.1, and 46.1 mbsf, and oxygen isotope stages 8.4, 8.6–9.1, and 9.2, respectively. In all three peaks *T. nitzschioides* and *T. nitzschioides* var. *parva* follow the abundance pattern of total marine diatoms, while the number of resting spores remains low throughout (not evident in Fig. 4).

#### Assemblage Zone III (50–95 mbsf)

This zone is characterized by three medium abundance peaks of  $70\text{--}114 \times 10^5$  valves/g dry sediment at 52.2, 63.2, and 76.5 mbsf, and oxygen isotope stages 10.3, 12.1, and 13.15, respectively. *Thalassionema nitzschioides* and *T. nitzschioides* var. *parva* show

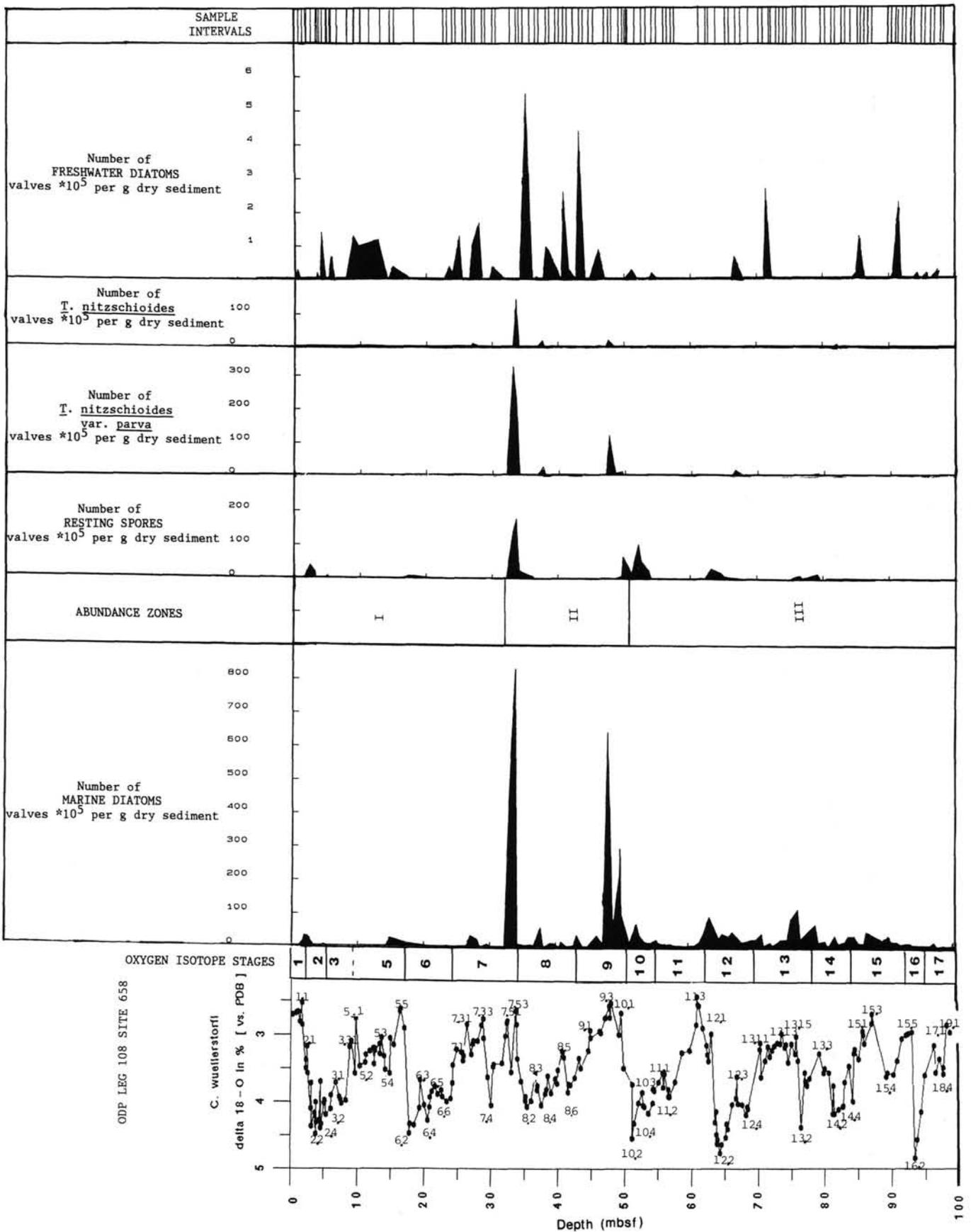


Figure 4. Late Quaternary downcore abundance of diatoms at Site 658. Depth (= composite depth) and  $\delta^{18}\text{O}$  stratigraphy from Sarnthein and Tiedemann (this vol.).

a small increase in these samples, but their highest abundances occur at 82.2 and 66.7 mbsf, respectively (with oxygen isotope stages 14.2–14.3 and 12.3). Again, resting spores follow the abundance pattern of the total marine diatoms.

Freshwater taxa show a more even distribution than marine ones. There is, however, a tendency toward barren samples in the lower 50 mbsf. The upper 50 mbsf of the core has nine peaks with  $>1 \times 10^5$  freshwater diatom valves/g dry sediment, with a maximum of  $5.5 \times 10^5$  valves/g dry sediment at 35.2 mbsf. The part between 50 and 100 mbsf has only three such peaks, with a maximum of  $2.7 \times 10^5$  valves/g dry sediment at 71.4 mbsf.

## DISCUSSION

### Late Quaternary Marine Record

The two extreme abundance maxima coincide with peak interglacial times (oxygen isotope stages 7.5 and 9.3). Medium-sized abundance maxima occur in glacial stage 8 and at stage boundaries 9/10, 11/12, and 13/14. The abundance pattern (Fig. 5), although possibly biased by the sampling frequency, indicates a low abundance of marine diatoms from 238 k.y. to the present (oxygen isotope stages 7.2–1). The period from 238 to 650 k.y. is characterized by a medium abundance. It is assumed that maxima in marine diatoms, especially in their resting spores, can be interpreted as reflecting high productivity. Maxima in resting spores are associated with diatom abundance maxima at oxygen isotope stages 1.1–2.1, 5.4, 7.5, 9.3–10.3, 12.1, and 13.3 and seem to be associated with terminations. One can therefore infer that high productivity occurs at terminations.

Pokras (1987a) combines high loadings of his Factor 1 (primarily *Thalassionema nitzschioides* var. *parva*) and Factor 2 (dominated by *Pseudoenotia doliolus*) to characterize moderate to high productivity. He found that diatom productivity over the last 160,000 yr in the eastern equatorial Atlantic has been highest during glacial stages, and he related higher diatom productivity to more vigorous trade winds during glacial intervals. The discrepancy in the timing of the productivity maxima of Pokras (1987a) and the present investigation remains unsolved. At Site 658 *Pseudoenotia doliolus*, which is more common in the South Atlantic (Pokras and Molino, 1986), has only been found in low numbers.

*Thalassionema nitzschioides* var. *parva* is presently restricted to the equatorial region and might be considered a separate species (Schrader and Schuette, 1981). According to Pokras and Molino (1986), it is associated with the warm waters of normal ocean salinity and at least with moderate productivity. Van Iperen et al. (1987), however, associate it with the highly saline, warm water of the South Equatorial Counter Current (SECC) and with moderate to low nutrient levels. Therefore, its high abundance at Site 658 at 20°N (especially during oxygen isotope stages 7.5 and 9.3) is likely to be related to the present environmental regime in the equatorial region, probably warm, high saline surface water (van Iperen et al., 1987). High abundances of *T. nitzschioides* var. *parva* do not occur above stage 7 or below stage 9.

According to Pokras and Molino (1986), fluctuations in *T. nitzschioides* sensu stricto should reflect fluctuations in river runoff and the related supply of nutrients offshore from equatorial Africa. In general, the taxonomy of this species and its varieties needs to be revised to minimize conflicting and contradictory interpretations (Schrader and Schuette, 1981). Pokras and Molino (1986) relate *T. nitzschioides* to the influx of low-salinity runoff from Central African rivers (i.e., Zaire and Niger), and van Iperen et al. (1987) relate it to waters with lowered salinity and high diatom production.

*Thalassionema nitzschioides* occurs with a very high abundance only near the  $\delta^{18}\text{O}$  stage boundary 7/8 ( $>140 \times 10^5$  valves/g dry sediment). In this sample, however, all marine diatom groups show an extremely high abundance. Smaller peaks of this species ( $10\text{--}25 \times 10^5$  valves/g dry sediment) occur in  $\delta^{18}\text{O}$  stages 7, 8, 9, and 14. Except for a small *T. nitzschioides* abundance peak in stage 7, none of the peaks of *T. nitzschioides* corresponds to events of river runoff as determined by pollen (Dupont et al., this volume).

In a similar study of "Meteor" core I3521 (Stabell, 1986b) from the equatorial Atlantic, maxima in marine diatoms other than *Ethmodiscus rex* were also concentrated at the terminations. *Ethmodiscus rex* occurred as oozes in glacial stages 4 and 6. For core M13521, it has been suggested that this site had reduced upwelling intensity during periods of decreasing wind strength but nutrient conditions that favored marine diatoms other than *E. rex*. Also, in cores from the Norwegian Sea (Stabell, 1986a), diatom maxima occur at the Pleistocene/Holocene boundary (Termination 1b).

Common for all oceans at periods of deglaciation (i.e., terminations) is the rise of sea level. A transgression over the coastal areas would erode the sediments and enrich the ocean water with nutrients. Diatoms, as primary producers, would have increased productivity due to the greater availability of phosphate, nitrate, and silica, in particular. It is therefore possible that there is a relation between high diatom productivity and sea level rise. This will be discussed in detail in a forthcoming paper.

### Late Quaternary Freshwater Record

High abundances of freshwater diatoms ( $>1 \times 10^5$  valves/g dry sediment) mainly occur within interglacial stages ( $\delta^{18}\text{O}$  stages 3.3, 5.1–5.2, 7.1 and 7.3, 13.1, and 15.1 and 15.5; Figs. 4 and 5). There is a tendency for the freshwater diatoms to occur at periods of ice growth such as found in Meteor cores I3519 and I3521 (Stabell, 1986b), with fairly large peaks occurring near stage boundaries 2/3 and 8/9. The largest peak, however, occurs near stage boundary 7/8 (Fig. 5).

The freshwater diatom floras found at Site 658 are quite diverse, compared with the freshwater assemblages reported from marine cores closer to the equator, which are totally dominated by the taxon *Aulacoseira (Melosira) granulata*. It is possible that this difference reflects differences in dissolution. However, it may also reflect that the freshwater diatoms near Cap Blanc are derived from a different area than the ones found near the equator (see also Gasse et al., in press).

### Pliocene Freshwater Record

The Pliocene freshwater diatom record is shown vs. age in Figure 6. The freshwater diatom flora in this part of the core is dominated by *Aulacoseira granulata*. Between 3.5 and 2.8 Ma, freshwater diatoms were found in most samples (24/33 = 72.7%). Thirteen of these samples contained  $\geq 0.5 \times 10^5$  freshwater diatom valves/g sediment. At about 2.8 Ma, the input of freshwater diatoms decreases significantly. Between 1.6 and 2.8 Ma, 20 out of 27 samples (= 76%) are barren of freshwater diatoms, and only 1 of these samples (2.46 Ma) contained  $>0.5 \times 10^5$  freshwater diatom valves/g sediment. In the 2 m.y. covered by this investigation, high abundances ( $\geq 1 \times 10^5$  freshwater diatom valves/g sediment) were found at 3.53, 3.24, 3.05, 2.84, and 2.46 Ma.

The general trend in the Pliocene record of freshwater diatoms at Hole 658 is a general transport of freshwater diatoms to the site prior to 2.8 Ma, but with a pronounced frequency decrease afterward. The interval between 3.5 and 2.8 Ma shows a distribution pattern similar to the one during the last 700,000 yr (Fig. 3). The sample density is, however,

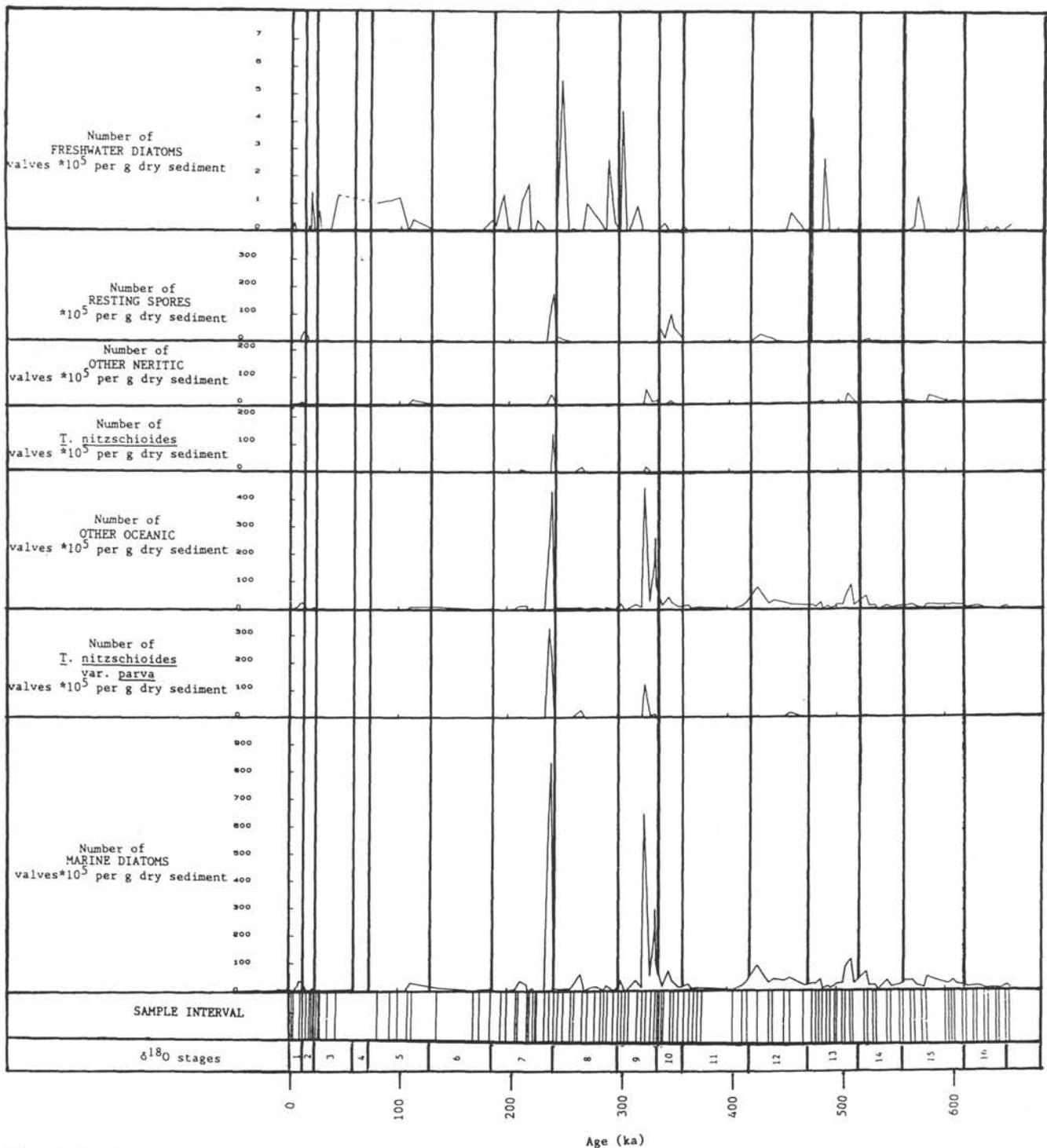


Figure 5. Late Quaternary diatom abundance vs. time at Site 658. The time scale is based on the oxygen isotope stratigraphy (see Fig. 4).

much higher in the Pleistocene part (average sample interval = 7,000 yr) than in the Pliocene (average sample interval = 30,000 yr).

The frequency pattern of freshwater diatoms during the period from 3.6 to 2.8 Ma may either be interpreted as reflecting a period with strong trade winds bringing freshwater diatoms out over the Atlantic Ocean or a period with large rivers transporting freshwater diatoms into the ocean.

If eolian transport is assumed, the climate might have been arid or there might have been diatomaceous deposits subject

to erosion. Sarnthein et al. (1982) and Stein (1985) found that increased trade winds and intermittent strong phases of aridity (North Saharan) commenced at about 3.2 Ma and intensified at about 2.45 Ma. Tiedemann et al. (this volume) found that South Saharan aridity commenced even earlier (4 Ma). If freshwater diatoms are used as an aridity signal, the freshwater diatoms from the investigated Pliocene part of Hole 658 reflect an arid climate up to 2.8 Ma, followed by a more humid climate from 2.8 to 1.6 Ma. The aridity cycles at about 3.53,

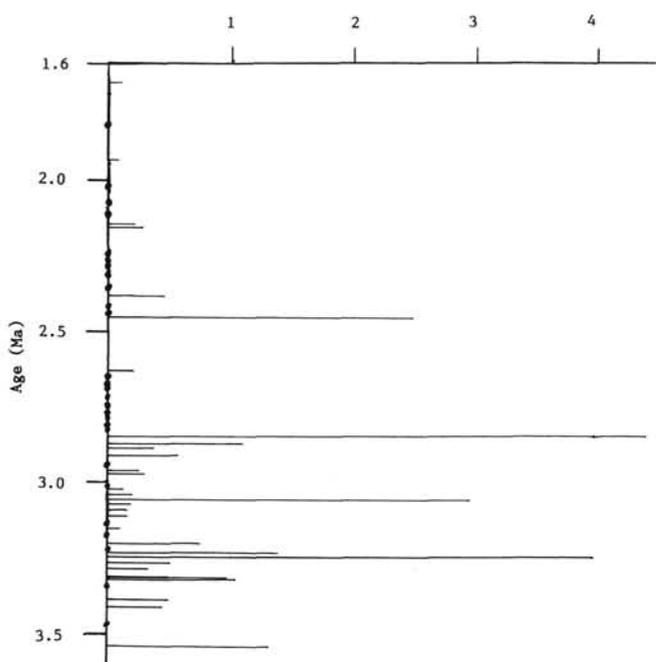


Figure 6. Pliocene freshwater diatom abundance vs. time at Site 658 (valves  $\times 10^5$  valves/g dry sediment).

3.24, 3.05, 2.84, and 2.46 Ma coincide with glacial periods according to the  $\delta^{18}\text{O}$  curve (Tiedemann and Sarnthein, this volume). Due to the coarse sampling interval, no attempt was made to search for cyclicity.

The Pliocene freshwater diatom record at Site 658 shows an amplitude pattern opposite to those from Sites 662 and 664 (Pokras, 1987b). It is possible that the two diatom records indeed reflect the same climatic story. Both sites would have received very few freshwater diatoms by eolian transport, but Site 658, being close to the shore, would have received large amounts of fluvial-transported freshwater diatoms. The increased aridification amplitude starting around 2.5 Ma cannot be seen at Site 658, however.

If fluvial transport is assumed, the climate would have been humid prior to 2.8 Ma. There is evidence for a humid climate with large rivers in the area; however, a long-term dry up of fluvial runoff from the Central Sahara possibly occurred about 3.2–2.9 Ma (Tiedemann et al., this volume). The Pliocene freshwater diatom flora at Hole 658 is dominated by *Aulacoseira granulata*, which is common in large rivers and in the lakes along the southern edge of the Sahara. The lakes of Central and North Sahara, however, are characterized by a more diverse flora. Larger numbers of freshwater diatoms than for the present study will have to be counted in order to detect possible river indicators.

### CONCLUSION

High abundances ( $>1.2 \times 10^7$  valves/g dry sediment) of marine diatoms occur in interglacial stages (7.5 and 9.3). Medium-sized abundance maxima ( $0.5\text{--}1.2 \times 10^7$  valves/g dry sediment) of marine diatoms occur at oxygen isotope stages 8.4, 9.3, 10.1, 10.3, 12.1, 13.1, 13.3, and 14.1. There is a tendency for these maxima to occur at Younger Dryas events (10.1, 12.1, and 14.1). Small- to medium-sized abundance maxima of marine diatoms tend to occur near the stage boundaries (1/2, 5/6, 9/10, 11/12, and 13/14). Late Quaternary freshwater diatoms mainly have their maxima in interglacial

stages, and the Pliocene diatom record indicates a frequency decrease at 2.8 Ma.

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