Ruddiman, W., Sarnthein M., et al., 1989
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 108

9. EVOLUTION OF SOUTH SAHARAN/SAHELIAN ARIDITY BASED ON FRESHWATER DIATOMS (GENUS *MELOSIRA*) AND OPAL PHYTOLITHS: SITES 662 AND 664[1]

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ABSTRACT

The record of windblown, siliceous microfossils at Ocean Drilling Program Sites 662 and 664 indicates that aridity cycles in tropical North Africa have existed for at least 3.8 Ma. Their presence reflects intermittent diminution in monsoon rainfall over the southern Sahara and Sahel, leading to the increased eolian transport of microfossils in Northern Hemisphere winter. Evidence generated thus far is compatible with an increase in the severity of arid events and/or a decrease in the strength of humid events ~2.3–2.5 Ma ago. An increase in the intensity of atmospheric circulation may also have occurred. Our data show no convincing evidence for major long-term changes in North African climate since that time.

INTRODUCTION

The arid climate of North Africa is largely a result of two meteorological factors. First, atmospheric downwelling at the northern boundary of the Hadley cell leads to a large excess of potential evaporation over precipitation (Nicholson and Flohn, 1980). Second, the Sahara lies under the Tropical Easterly Jet, a regime of upper-tropospheric easterly winds (Hastenrath, 1985). The Tropical Easterly Jet is a seasonal phenomenon that inhibits penetration of moist winds from the equatorial Atlantic (the African monsoon) into the interior of North Africa in Northern Hemisphere summer. Variations in monsoon circulation, and thus in North African aridity, can result from a number of factors, including changes in the intensity or position of the Hadley cell and fluctuations in the strength of the Tropical Easterly Jet.

Because land-based records of long-term climatic change in North Africa are incomplete and often difficult to date, most such information has come from deep-sea sediments. Sarnthein et al. (1982) and Stein (1985) have summarized past research on the Neogene history of North Saharan aridity. They identified several intervals of increased aridity within the last 25 Ma, with the latest phase beginning ~3.2 Ma ago and intensifying ~2.4 Ma ago and again near the Brunhes-Matuyama boundary ~0.73 Ma ago.

Siliceous microfossils derived from tropical Africa and transported to the equatorial Atlantic by wind action have been reported for over a century (e.g., Darwin, 1846; Kolbe, 1957; Parmenter and Folger, 1974). Transport from the southern Sahara and the Sahel to the equatorial Atlantic occurs primarily in Northern Hemisphere winter, at altitudes of ~1–4 km (see Prospero, 1981, figs. 10 and 11). Recently, freshwater diatoms of the genus *Melosira* (= *Aulacosira*) and opal phytoliths have proven highly useful as recorders of large-scale fluctuations in the climate of Saharan and sub-Saharan Africa during the late Pleistocene (Pokras and Mix, 1985, 1987; Stabell, 1986). Pokras and Mix (1987) demonstrated a strong 23,000-yr periodicity in the transport of *Melosira* valves to the equatorial Atlantic; they interpreted this as indicative of fluctuations in the intensity of the African monsoon.

One of the goals of Ocean Drilling Program (ODP) Leg 108 was to extend these proxy records back into the Neogene in order to improve our understanding of the evolution of arid climates in tropical North Africa. This paper examines the records of these land-derived microfossils at equatorial Sites 662 and 664 (Fig. 1). Our primary intent is to determine when the eolian influx of siliceous microfossils to the equatorial Atlantic began. This date should coincide with the onset of cyclical variations in the aridity of the southern Sahara and Sahel. A second goal is to identify major events in the development of North African aridity. Ruddiman and Janecek present a related study of eolian lithogenic input to Sites 662, 663, and 664 in this volume.

Data presented in this study represent an initial attempt to reconstruct major events in the long-term history of North African aridity cycles. Due to the coarse sampling intervals employed here, we are not able to detect shorter term phenomena, such as orbital-scale cycles.

METHODS

This study used two types of samples, which were prepared and analyzed somewhat differently. Core-catcher samples from Holes 662A and 664D were prepared and examined semiquantitatively as described by Baldauf and Pokras (this vol.). Similar counts were made for 25 additional samples from the Pliocene section of Hole 662A. Stratigraphic control was based on biostratigraphic and magnetostratigraphic datums presented in the site reports for Sites 662 and 664 (Ruddiman, Sarnthein, et al., 1988).

In addition, we examined the Pliocene section of Hole 664D quantitatively and with increased sampling density. Preparation and counting followed a technique modified from that of Schrader and Gersonde (1978). A measured amount of material (~0.2 g of oven-dried sediment) was placed in a 250-ml beaker. We added 10 ml each of 35% H_2O_2 and 30% HCl and boiled the mixture until it turned yellow. Distilled water was added to total 200 ml; the mixture was then allowed to rest for 1 hr.

The supernatant was decanted and discarded, taking care not to disturb the material that had settled out. The beaker was refilled to 200 ml with distilled water, and the decantation repeated a total of seven times. On the last decantation, a maximum of 25 ml was left in the beaker. Distilled water was added, if necessary, to total exactly 25 ml. Immediately after stirring the sample to assure uniform distribution of sediment, a measured amount of suspensate was removed with a precalibrated pipette and transferred to a cleaned 22- × 22-mm cover slip. This material was left to air dry at room temperature. The cover slip was then inverted and mounted on a microscope slide using

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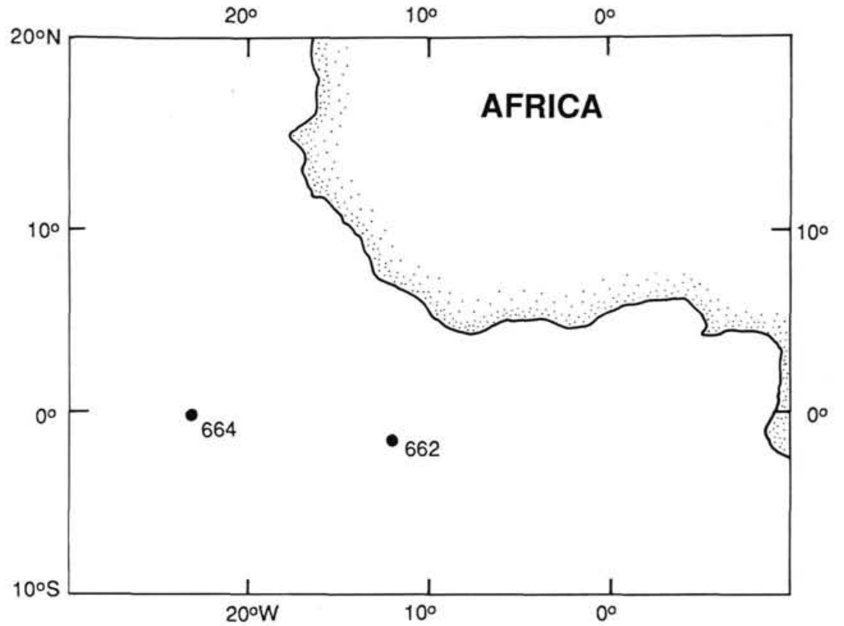

Figure 1. Location of Sites 662 and 664 cored during Leg 108.

Permount B medium. Finally, the slide was heated to boiling until the medium ceased to bubble, which ensured a permanent mount. Two slides were made for each sample.

Quantitative counts were made at 160×, using a Zeiss compound microscope. Two parallel tracks were counted near the center of each slide in both horizontal and vertical directions. This method allowed rapid counting, as both *Melosira* valves and phytoliths are easily identified even at such relatively low power. It also provided acceptable statistical reproducibility (~20% at the 95% confidence level except where abundances are below ~2000/g). The use of traverses across the middle of the slide is likely to result in overestimates of true abundance by up to 20% (Schrader and Gersonde, 1978). Critically, however, it does maintain the internal consistency of our results. Unlike the method described by Pokras and Mix (1985), only whole *Melosira* valves were counted, so that the numbers in the two studies are not directly comparable.

Because of the lack of detailed data on sedimentation rates, we were not able to convert per-gram data to absolute accumulation rates. Preliminary stratigraphy suggests that long-term sedimentation rates do not vary substantially (Ruddiman, Sarnthein, et al., 1988). In piston core V30-40, near the location of Site 664, a close covariance exists between per-gram abundances and accumulation rates of *Melosira* valves (Pokras and Mix, 1987). Thus, we will use per-gram numbers as first-order substitutes for accumulation rate data.

The variability in *Melosira* time series from the equatorial Atlantic is concentrated at frequencies at and below 23,000 yr (Pokras and Mix, 1987). Time series of phytoliths also suggest high-frequency changes (Pokras and Mix, 1985; Stabell, 1986). Thus, our records are strongly aliased because our sampling intervals are much too coarse to detect such rapid fluctuations. Similarly, we may have failed to detect short-lived increases in input (Pisias and Mix, 1988). The records presented here are appropriate, therefore, only for developing a general overview of changes in North African aridity.

RESULTS

Semiquantitative Data

We generated semiquantitative data from core catchers in Holes 662A (Fig. 2A) and 664D (Fig. 2B) through the last 4 Ma, as well as several additional samples near the bottom of Hole 662A (Fig. 2A). Sampling intervals average approximately 219,000 yr in Hole 662A (~58,000 yr prior to ~1.7 Ma) and 181,000 yr in Hole 664D. Samples 108-662A-5H-CC, 108-662A-6H-CC, 108-662A-10H-CC, and 108-662A-11H-CC, which represent slumps or turbidites, were excluded from this analysis.

In addition to data on *Melosira* and phytoliths, we present a semiquantitative estimate of marine-diatom abundance and preservation for each sample level. This is done as a first-order index of total opal content because large changes in the overall input of silica could control the preservation of land-derived, siliceous fossils and thus lead to a spurious signal based on preservation rather than input. Trends in *Melosira* or phytolith abundance that were identical to trends in marine-diatom abundance would be particularly suspect.

In Hole 662A, no such correspondence is evident for either *Melosira* valves or phytoliths prior to ~2.0 Ma (Fig. 2A). Marine diatoms occur consistently throughout the record, whereas *Melosira* valves and phytoliths occur respectively in approximately one-half to one-third of the samples. Therefore, we can rule out a preservational effect on *Melosira* and phytolith numbers before 2.0 Ma at Site 662.

Although all three quantities are generally higher after 2.0 Ma than before that time, *Melosira* valves decrease in numbers in the last 0.8 Ma, while marine diatoms are at their most abundant. This suggests that abundances of marine diatoms do not control *Melosira* and phytolith numbers in the upper portions of the records. In general, the variability of *Melosira* and phytolith numbers increases with sampling density, which emphasizes the presence of short-term fluctuations in the records.

A noteworthy change occurs in the *Melosira* curve at ~2.5 Ma. Only 1 of 15 samples older than that contain at least a few *Melosira* valves, and 6 of the 15 are barren of these fossils. From 2.5 Ma to the core top, 14 of the 26 samples contain at least a few *Melosira* valves, and only 3 are barren of *Melosira* valves. In spite of the obviously aliased nature of the record, it is unlikely that such a marked difference is entirely an artifact.

The aliasing of the record does, however, make it impossible to determine the exact timing of this change, so the assigned date of 2.5 Ma may not represent the exact timing of the increase in eolian input. Specifically, the maximum at

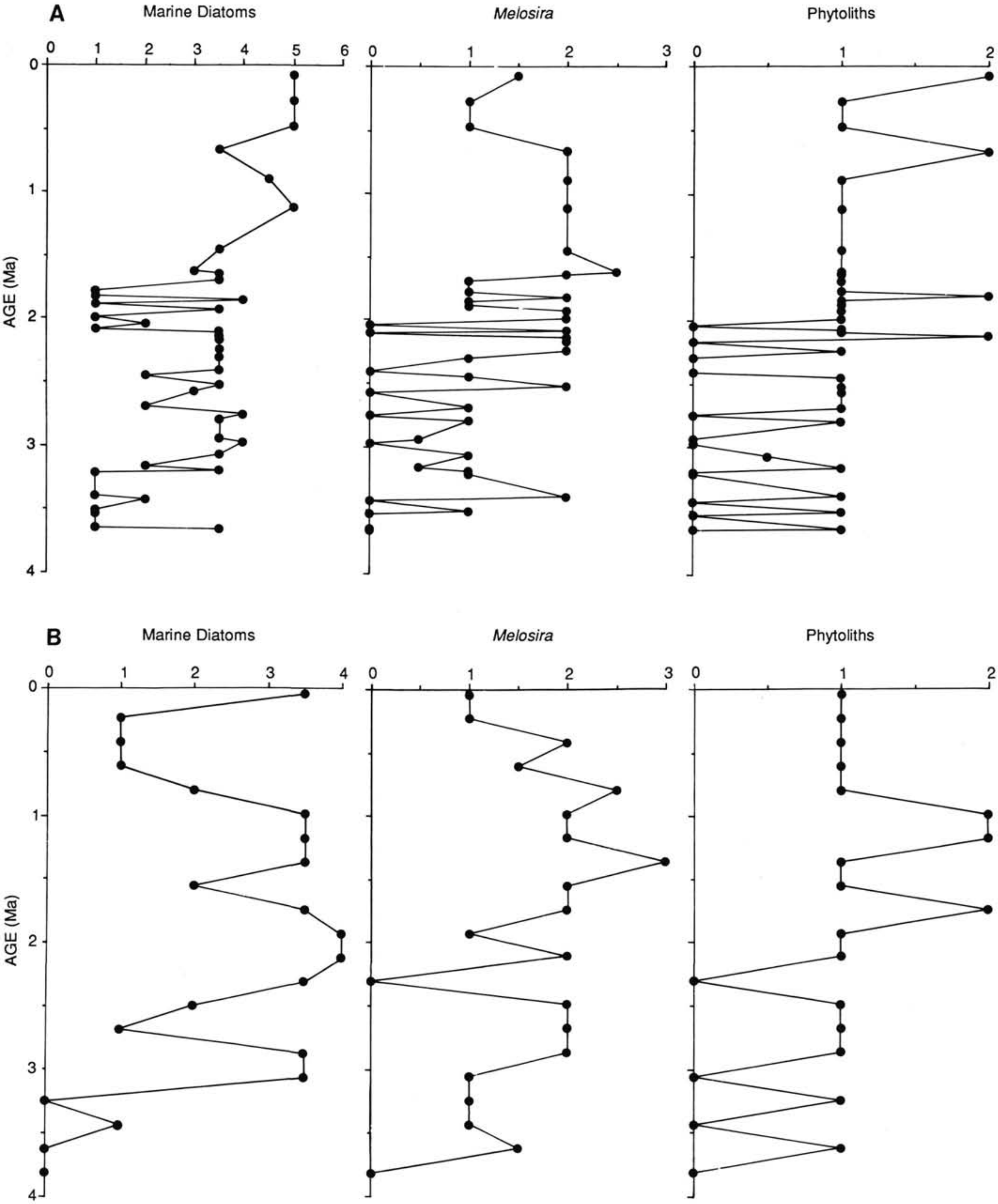

Figure 2. Abundance of marine diatoms, *Melosira* valves, and phytoliths in Holes 662A (**A**) and Hole 664D (**B**) through the last 4 Ma. Numbers represent the abundance of fossils, as well as the preservation of marine diatoms. For marine diatoms, 0 = barren; 0.5 = very rare, poor; 1 = rare, poor; 1.5 = rare to few, poor; 2 = few, poor; 2.5 = few, moderate; 3 = few to common, poor; 3.5 = common, poor; 4 = common, moderate; 4.5 = abundant, poor; and 5 = abundant, moderate. For *Melosira* valves and phytoliths, 0 = barren; 0.5 = very rare (one per slide); 1 = rare; 1.5 = rare to few; 2 = few; 2.5 = few to common; and 3 = common.

~2.5 Ma is followed by two samples with rare *Melosira* and one with none. After this, *Melosira* valves return to generally high numbers. Thus, the maximum at ~2.5 Ma could represent a transient event, with the major climatic change indicated closer to 2.3 Ma. We cannot choose between these alternatives with the present, aliased records.

In Hole 664D, *Melosira* valves and phytoliths both appear for the first time ~3.8 Ma ago (Fig. 2B). We do not show 11 core catchers older than 4 Ma; all are barren of diatoms and phytoliths. The initial occurrence of marine diatoms and windblown microfossils at nearly the same time suggests a possible preservational effect. Higher in the section, however, abundances of marine vs. windblown microfossils do not correspond. As in Hole 662A, there appears to be a decrease in *Melosira* numbers in the late Pleistocene (the last 700,000 yr). On the other hand, phytolith curves for the 2 cores are very different.

In both cores, all samples with few or no whole *Melosira* valves are also either barren or nearly barren of *Melosira* fragments. Thus, we can exclude the possibility that variations in the numbers of whole *Melosira* valves are controlled by fragmentation during transport and burial or during sample processing.

Pliocene Section, Hole 664D

Per-gram abundances of *Melosira* valves and phytoliths in Holes 664D were determined from 4.25 to 1.75 Ma, at an average sampling interval of 58,000 yr (Fig. 3). Again, the initial occurrence of both types of specimens near 3.8 Ma is evident. An increase in the amplitudes of both *Melosira* and phytolith maxima occurs at ~2.5 Ma, with increased variability in both records after that time. An argument that this increase is real in spite of aliasing can be made on a statistical basis. Only 1 of 24 counts older than 2.5 Ma exceeds 10,000 *Melosira* valves per gram, whereas 5 of 16 counts younger than 2.5 Ma exceed that value. It is unlikely that the difference in the frequency of high *Melosira* counts before vs. after 2.5 Ma (~4% vs. 31%) is entirely an aliasing artifact.

DISCUSSION

The supply of *Melosira* valves to the deep sea indicates substantial fluctuations in the land climate. Specifically, an interval of humid climate must occur so that lakes can expand and freshwater diatom production flourish. An arid interval must then ensue, resulting in the exposure of lake beds and diatom fossils to deflation by winds (Pokras and Mix, 1985, 1987; Stabell, 1986).

This type of climatic fluctuation can result from alternate strengthening and weakening of the African monsoon. The occurrence of phytoliths in deep-sea sediments indicates that the continental climate must be moist enough to allow grasses to grow at least seasonally, but also dry enough that bush fires can occur during the dry season and therefore inject phytoliths into the atmosphere (Pokras and Mix, 1985).

The presence of both *Melosira* valves and phytoliths 3.8 Ma ago in Hole 664D indicates that the eolian supply to the equatorial Atlantic, and hence intermittent aridity in the southern Sahara and Sahel, began at least 0.6 Ma earlier than suggested by Sarnthein et al. (1982) and Stein (1985), based on rotary-cored records from farther north than Sites 662 and 664. The hydraulic piston corer (HPC) records from 18°–21°N (summer dust plume) presented by Tiedemann et al. (this vol.), in contrast, indicate arid conditions in the Sahara as early as 4.3–4.7 Ma.

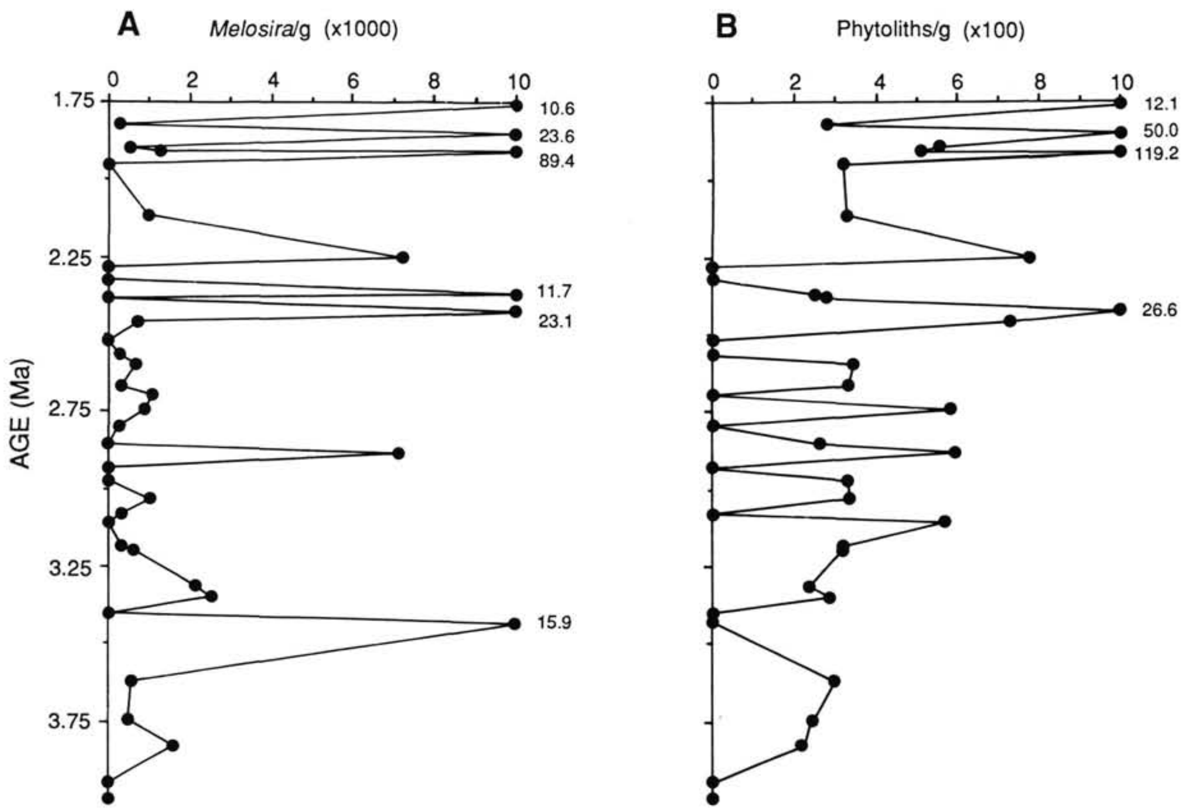

Figure 3. Per-gram abundances of windblown, siliceous microfossils in Hole 664D, 1.75–4.25 Ma. **A.** Melosira valves. **B.** Phytoliths.

The earlier appearance of aridity north of 18°N may indicate that dust in the cores examined by Tiedemann et al. (this vol.) comes from a more northerly source than the dust in Sites 662 and 664. These findings and ours point to at least intermittent weakening in the monsoon flow from the equatorial Atlantic into the interior of North Africa since the early Pliocene. Because our records are aliased, it is too early to speculate on the reality or significance of the results of this study and those of Tiedemann et al. (this vol.).

All 11 core-catcher samples in Hole 664D older than 3.8 Ma are barren of marine diatoms as well as *Melosira* valves and phytoliths, so the absence of land-derived siliceous microfossils could be due to dissolution rather than to a lack of supply. Thus, our data could underestimate the antiquity of arid episodes in tropical North Africa. Sites 662 and 663 do not penetrate far enough back in time to bear on this issue, and corroborative data on eolian, lithogenic influx to Site 664 prior to 3.6 Ma are not yet available.

Maley (1980) has summarized continental evidence for the aridification of North Africa during the Pliocene. Data include lower Pliocene eolian deposits in southern Egypt, desertlike faunas and floras in the northern Chad area between 4 and 5 Ma ago, and indications of a strongly fluctuating climate in the Chad basin. The fragmentary nature of Pliocene deposits from North Africa makes it difficult to establish precise correlations between marine and continental records, so it is not clear whether or not the apparent 3.8 Ma aridification event seen at Site 664 reflects the same aridification events found on land.

Marine and continental records do, however, appear to agree that aridity was increasing in the early Pliocene. The fact that *Melosira* and phytolith maxima are generally of a lower amplitude prior to 2.3–2.5 Ma than after that time indicates that the eolian supply was still limited. It also indicates either that aridity maxima were relatively modest until the late Pliocene or that the areas where arid conditions first occurred were more distant from Sites 662 and 664 (perhaps farther east).

Ruddiman and Janecek (this vol.) report a substantial increase in eolian input of lithogenic sediment to Sites 662/663 approximately 2.4 Ma ago. In spite of our aliasing problems, we see some indication that the influx of *Melosira* valves and phytoliths to Site 664 increases at approximately that time. This coincides with the onset of significant glaciation in the Northern Hemisphere, as dated by Shackleton et al. (1984) and Ruddiman et al. (1986). It is not clear why no corresponding increase in eolian input to Site 659 is evident (Tiedemann et al., this vol.).

The consistent presence of phytoliths after 2.0 Ma implies at least moderate aridity in the south Saharan/Sahelian region during the last 2.0 Ma, with a seasonal cycle large enough to support both growth and desiccation of grasslands at different times of year. Alternatively, this fact may reflect alternating intervals of several wet years and several dry years.

Eolian influx of lithogenic material to Sites 662/663 and 664 has decreased substantially in the past ~800,000 yr (Ruddiman and Janecek, this vol.). This suggests that the decrease in numbers of *Melosira* at both Sites 662 and 664 in the last ~700,000 yr may be real, in spite of aliasing.

Changes in the intensity of Saharan/Sahelian aridity cycles reflect the waxing and waning of the African monsoon (Pokras and Mix, 1985; Stabell, 1986; Prell and Kutzbach, 1987). Thus, our results indicate that monsoon circulation in the southern Sahara and Sahel was more intense prior to ~3.8 Ma ago and, hence, that the continental climate was more humid. Although a change in the strength of monsoon circulation suggests a substantial change in the earth's climatic system, the exact mechanism is not yet clear.

Because of the close temporal correspondence of increased *Melosira* influx at Sites 662/663 and 664 with increased glaciation at high northern (e.g., Shackleton et al., 1984) and southern (e.g., Ciesielski and Grinstead, 1986 and references therein) latitudes, all at approximately 2.4–2.5 Ma, we tentatively suggest that aridity in the south Saharan/Sahelian region may respond to forcing from higher latitudes.

CONCLUSIONS

An examination of siliceous microfossils of North African origin allows us to reconstruct the broad features of monsoon circulation in tropical North Africa over the last 4 Ma. The onset of arid climatic events occurred not less than 3.8 Ma ago. There may have been an increase in the intensity of arid episodes ~2.3–2.5 Ma ago, coinciding with an increase in the variability of terrigenous input and presumably with an increase in the variability of monsoon circulation and thus of climate in Saharan and sub-Saharan Africa. Events since 2.3–2.5 Ma have been less dramatic; because of the highly aliased nature of the data presented here, no firm conclusions can be made about long-term changes in North African climate since that time.

ACKNOWLEDGMENTS

We are thankful to Aram Derewetzky for laboratory assistance and drafting, and to Lloyd Burckle and Andy McIntyre for reviews. Funding from USSAC funds, and from NSF grant OCE87-00505 to E.M.P., is also gratefully acknowledged. This is Lamont-Doherty Geological Observatory Contribution No. 4473.

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Date of initial receipt: 8 March 1988
Date of acceptance: 12 February 1989
Ms 108B-128