Wefer, G., Berger, W.H., Richter, C., et al., 1998
*Proceedings of the Ocean Drilling Program, Initial Reports,* Vol. 175

# 22. COLOR CYCLES IN QUATERNARY SEDIMENTS FROM THE CONGO FAN REGION (SITE 1075): A STATISTICAL ANALYSIS[1]

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**ABSTRACT**

Color reflectance (red/blue ratio) and total reflectance show characteristic cycles in olive-gray sediments from the Congo Fan region (Ocean Drilling Program Site 1075). To test the hypothesis that these are productivity cycles with a precessional periodicity, we constructed a detailed age model based on matching the magnetic susceptibility record to an oxygen-isotope standard from the Ontong Java Plateau (OJsox96). The fit is excellent for sedimentation rates near 100 m/m.y., especially if the susceptibility data are processed by partial forward integration (assuming that peaks in susceptibility are associated with sea-level rise). The age model thus derived allows a study of spectra and phase of the color cycles. The red/blue ratio has indeed strong precessional power (as expected for productivity cycles in this region), which is especially pronounced in the last 500 k.y. Total reflectance displays the characteristic beat pattern from eccentricity modulation. Obliquity cycles are present in the last 350 k.y., but they are subdued. This indicates that monsoonal forcing is much more important here than high-latitude forcing in producing lithologic changes expressed as sediment color.

## INTRODUCTION

The cyclic nature of Quaternary sedimentation in the deep ocean has been well established since the Swedish Deep-Sea Expedition. It is evident in the carbonate patterns of the tropical Pacific (Arrhenius, 1952) and in the deposition of terrigenous sediments in the North Atlantic (Ericson et al., 1961). The color of sediments changes in response to the cyclic changes in composition, in some places markedly (as in the contrast between white oozes and brown clay), in others more subtly (in hues of green or brown). Such changes in color have recently become important in cyclostratigraphic studies and as a tool for correlation of cores from adjacent holes at Ocean Drilling Program (ODP) sites (Busch, 1991; Mix et al., 1992, 1995; Hagelberg et al., 1992; Schneider et al., 1995). Other physical properties, such as bulk sediment density, magnetic susceptibility, and velocity, also are useful in this context (e.g., Mayer, 1991; Herbert and Mayer, 1991). In many cases, color changes are a result of changes in the abundance of organic carbon, which, in turn, are tied to glacial/interglacial productivity cycles (Müller et al., 1983). These are the type of color cycles we analyze in this study.

Here we present a preliminary statistical analysis of color and magnetic susceptibility cycles in ODP Site 1075, which was drilled during Leg 175 in the Lower Congo Basin, along the northern rim of the Congo Fan, off the Congo River, the second largest river in the world (Peters, 1978). The recovered sediment consists entirely of greenish gray to olive-gray clay with varying amounts of nannofossils and diatoms. The ~200-m-long record spans more than the last 2 m.y., with the overall sedimentation rate just less than 100 m/m.y.

We aim to show that the physical properties of these sediments can be used to refine the age scale, and that such refinement can bring out cyclic properties in color and reflectance that are useful in developing conceptual models about the dynamics of the regional sedimentary province. These concepts can guide further research regarding the origin of the cycles and the climate-related messages they contain. Results of our analysis suggest that such messages are complicated by changes in the processes dominating the expression of physical properties through time. Nevertheless, clues to changes in the relative influence of high- and low-latitude forcing on the dynamics of regional sedimentation (characterized by different cycles) can still be recognized. In particular, we identify differences in the influence of cryocyclic variations, with periods of 100 k.y. and 41 k.y., and monsoonal variations, with periods near 21 k.y., for different properties and over different time periods.

## GEOLOGICAL SETTING AND BACKGROUND

The regional environment of Site 1075 (as well as companion Sites 1076 and 1077) is dominated by three major influences: (1) the freshwater input from the Congo River, (2) seasonal coastal upwelling and associated filaments and eddies moving offshore, and (3) incursions of open-ocean waters, especially from the South Equatorial Countercurrent (see "Background and Objectives" section, "Site 1075" chapter, this volume). According to Jansen (1985), river-induced phytoplankton activity extends ~160 km beyond the shelf edge, thus affecting Site 1075. However, much or most of the regionally enhanced productivity is not river related. Divergence and doming, as well as cyclic interactions between the South Equatorial Countercurrent and the Benguela Current, may be the dominant factors.

The high (near 100 m/m.y.) and comparatively steady sedimentation rate is a result of a sustained high supply of fine-grained suspended material from the river and the high productivity of overlying waters. Calcareous microfossils are only a minor constituent; on the whole, concentrations rise toward the present, with maxima in mid-Brunhes time. The biosiliceous fraction has a concentration similar to terrigenous clay. The sediments are rich in organic matter (typically 1–4 wt%), with sulfate reduction leading to complete removal of sulfate in the upper 30 m. Correspondingly, pyrite is ubiquitous at this site (see "Lithostratigraphy" section, "Site 1075" chapter, this volume).

The bulk of the sediment delivered by the Congo River bypasses the area of Site 175, moving down-canyon to feed the channel-and-

[1]Wefer, G., Berger, W.H., Richter, C., et al., 1998. *Proc. ODP, Init. Repts.,* 175: College Station, TX (Ocean Drilling Program).

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levee systems of the Congo Cone. The canyon is unusual in that it cuts deeply across the shelf, with water depths of several hundred meters, extending far into the lower stretches of the river (Peters, 1978; Eisma and van Bennekom, 1978).

Whatever the mix of factors dominating the sediment patterns, they are expected to change through time and in a cyclic fashion (Jansen et al., 1984; Olausson, 1984; Zachariasse et al., 1984; Jansen, 1985; Schneider et al., 1997). Our analysis will show that the nature of these cycles is complex.

## DATABASE AND METHODS

The raw reflectance record of Site 1075, measured at intervals of 4 cm (2 cm in some parts and modified to void space) displays pronounced periodicity in the red/blue ratio at all three holes cored (Fig. 1). Total reflectance shows somewhat similar cycles, albeit less pronounced (Fig. 2). Reflectance of visible light (thirty-one 10-nm-wide spectral bands from 400 to 700 nm) was measured with a Minolta CM-2002 spectrophotometer on split-core surfaces that were covered with a thin, transparent plastic film (e.g., Schneider et. al, 1995).

Preliminary estimates of the time scale, based on biostratigraphic analysis, immediately suggest a strong component of the 23-k.y. precession cycle in the red/blue ratio (see "Lithostratigraphy" section, "Site 1075" chapter, this volume). Variations in the ratio of the red-to-blue wavelengths are weakly correlated with the concentration of organic carbon, but show little or no covariation with concentrations of calcium carbonate (Fig. 3). Also, no correlation with total sulfur was found. The pronounced cyclicity in the precessional band suggests a strong influence of productivity variation. The connection between precession and productivity is well established for late Quaternary sediments in this area (Schneider et al., 1994, 1997).

## STACKING OF DATA SERIES AND AGE ASSIGNMENT

A detailed study of the periodicity of the color reflectance requires an accurate age scale. Clearly, to avoid circular reasoning, the reflectance record itself must not be used to derive this scale by orbital tuning. We therefore turn to magnetic susceptibility to explore the potential for tuning and matching to the global oxygen-isotope record. Magnetic susceptibility was measured on whole cores from the three holes as part of the multisensor track analysis that is standard on board the *JOIDES Resolution*. The susceptibility was quite low, usually between $1 \times 10^{-5}$ and $6 \times 10^{-5}$ (volume susceptibility in SI units; Fig. 4). Spuriously low values resulted from the numerous gas expansion voids present within the cores. Such expansion tends to be more common toward the bottom and top of a core. Thus, there may be a tendency for artificial cycles, generated by core breaks, within any one hole.

The available values were first reduced to a sampling interval of 8 cm (resolution near 1 k.y.), which was considered sufficient for the purpose of testing for cycles with periods >10 k.y. Values that had a range more than twice that of their neighbors in the previous 40 cm, counting downward in a core, were eliminated or reduced unless visual inspection showed similarly extreme values within the next 40 cm downcore. After thus despiking each record, it was smoothed by a five-point Gaussian filter. The in-core depth of each averaged value was then adjusted by using the identical filter.

As previously mentioned, in terms of providing for accurate measurements, the most valuable portion of each core is the mid-section. To produce a stacked record, we first aligned the characteristic features of individual core records from different holes (see "Composite Section" section, "Explanatory Notes" chapter, this volume; Hagelberg et al., 1992). The standard ODP depth scale can thus be converted into a meters composite depth scale, which represents the common

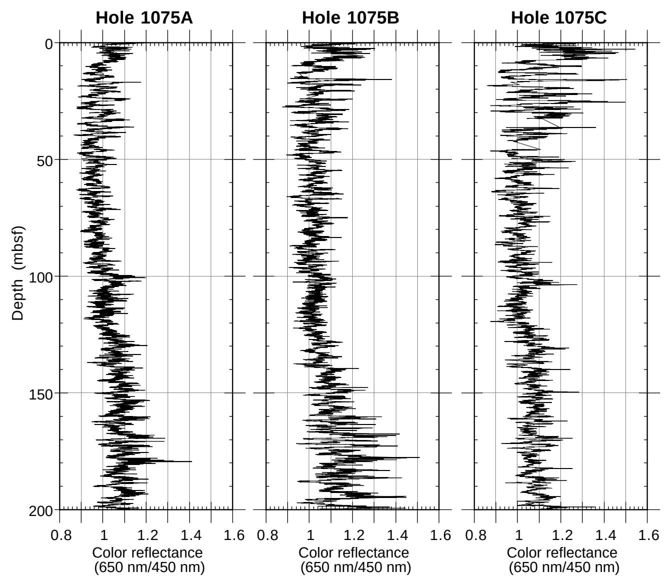


Figure 1. Color reflectance data (red/blue ratio) for Site 1075 (from "Lithostratigraphy" section, "Site 1075" chapter, this volume).

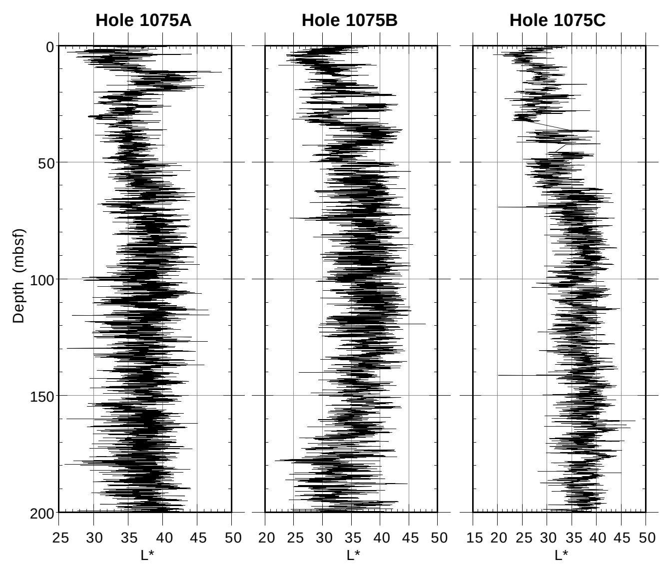


Figure 2. Total reflectance data for Site 1075 (from "Lithostratigraphy" section, "Site 1075" chapter, this volume).

depth scale for all three holes at one site. Coring gaps and sediment expansion during core retrieval result in a composite depth that is expanded compared with the driller's depth by about 10%. Each core was assigned a sinusoidal weighting function set to 0.03 at the top and bottom and to unity at the center. All individual magnetic susceptibility values, together with their weights, were then sorted for all three holes according to their assigned composite depths. Adjacent values in the sorted series were averaged three at a time, weighting each average according to the weights of the individual values for magnetic susceptibility being summed. The composite depth values were treated in an identical fashion. The end result of this procedure is a series of magnetic susceptibility values ordered according to composite depth and with information strongly biased toward measurements at the center of stacked cores.

Earlier work in the region around Site 1075 and preliminary estimates based on core-catcher examination suggested a sedimentation rate near 200 m/m.y. in the uppermost portion of the site, and one of about 100 m/m.y. overall. After an initial rough match of selected peaks and valleys of the magnetic susceptibility record to an oxygen-isotope record (described below), an equation describing total sedimentation rate as a function of composite depth was applied to the stacked record as follows:

$$\text{depth/age} = 28/\log(\text{depth} + 20) - 85/(\text{depth} + 20).$$

Based on this equation, preliminary ages were assigned to all composite depth values. The ages were then adjusted (mostly by increasing them between 12% and 20%) by matching the magnetic susceptibility curve to the oxygen-isotope record of Ontong Java Plateau (Berger et al., 1994; revised for the last 800 k.y. in Berger et al., 1996). This record is based on analysis of *Globigerinoides sacculifer* and is thought to represent sea-level change (having very little precessional component, in the middle of the tropics). The procedure yielded a depth for the Stage-20-to-Stage-19 transition at 82 meters below seafloor (mbsf), which agrees with the depth assignment for the Brunhes/Matuyama boundary (see "Paleomagnetism" section, "Site 1075" chapter, this volume). Considerable adjustment of initial age assignments was necessary for the uppermost cores from Site 1075, which appear to be greatly expanded. Amplitudes of magnetic susceptibility seem unusually high and were reduced by a factor of 2 for this section (~0–50 ka).

The match of magnetic susceptibility data to the oxygen-isotope curve (OJsox96; Ontong Java *G. sacculifer* oxygen isotopes, 1996) is excellent between 1.1 and 0 Ma (Fig. 5). This is especially true if the susceptibility series is partially integrated (labeled "partially integrated susceptibility" in Fig. 5A). The integration is by exponential decay of each value, from older to younger ages, with an e-folding time of 7000 yr. If this curve is the one to be correlated with oxygen isotopes, the entire scale needs to be adjusted by adding ~6000 yr. We have not done this, but this option should be kept in mind when considering phase relationships of the various cycles.

For the sediments older than about 1 Ma, it proved extremely difficult to find a satisfactory match, even after considerable experimentation. In the following text we will, therefore, largely restrict discussions to the periods within the last 1.2 m.y.; that is, the Milankovitch Chron (625–0 ka) and the Croll Chron (1240–625 ka; time scale of Berger et al., 1994).

The excellent fit of the magnetic susceptibility data to the oxygen-isotope curve should result in the appearance of Milankovitch power in the cycles of susceptibility. Fourier analysis of the autocorrelation series of OJsox96 (see Fig. 6) extracts the expected periodicities for the Milankovitch and Croll Chrons. The Milankovitch Chron shows the strong dominance of the ~100-k.y. cycle (with a peak near 98 k.y. related to eccentricity and internal oscillation) and a modest but clear 41-k.y. cycle (related to the changing obliquity of the Earth's axis). The Croll Chron does not show the 100-k.y. cycle but shows power near 80 and 140 k.y.

The cycles in the magnetic susceptibility record resemble those in the oxygen-isotope record, but they are by no means identical. The analysis yields strong periodicity near 100 and 41 k.y. for the last 500 k.y. (Fig. 7, bottom curve). The power near 70 k.y. represents the beat between these two periods (beat frequency = difference between the two base frequencies; that is, 1/41 – 1/98). The next older section (500 ka–1 Ma) shows only the 41-k.y. cycle (weakly) and a strong multiple of this cycle near 83 k.y. The spectrum of the next older section (1.0–1.5 Ma) suggests that the instantaneous sedimentation rate is overestimated here by about 10% (from the offset of the peak expected at 41 k.y.). The biostratigraphic data confirm this (see "Biostratigraphy and Sedimentation Rates" section, "Site 1075" chapter, this volume). The oldest section (1.5–2.0 Ma) seems strongly dominated by the 41-k.y. cycle.

## THE PATTERN OF COLOR CYCLES

We can now apply the age scale to the color series to obtain a first impression of the relationships between color and climatic change. A comparison with the oxygen-isotope record of the Milankovitch Chron is instructive (Fig. 8). It is the most familiar portion of the

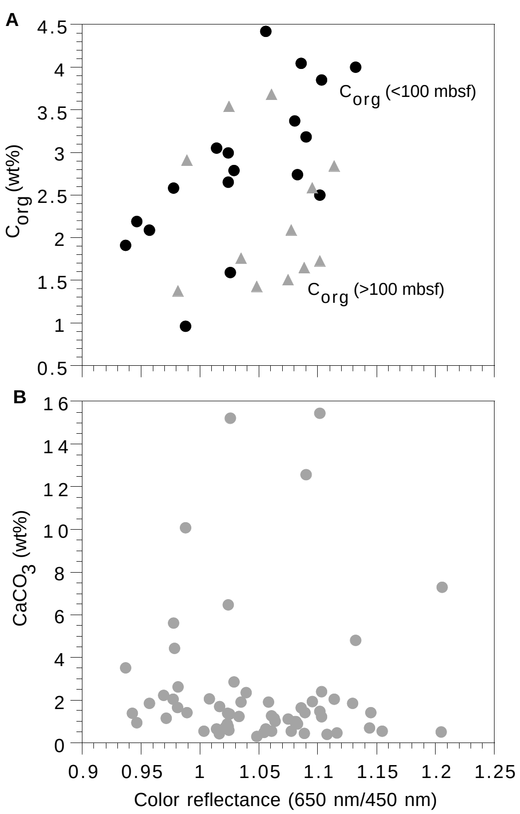


Figure 3. Relationship between color reflectance and (**A**) organic matter concentration and (**B**) carbonate in selected levels (from "Lithostratigraphy" section, "Site 1075" chapter, this volume).

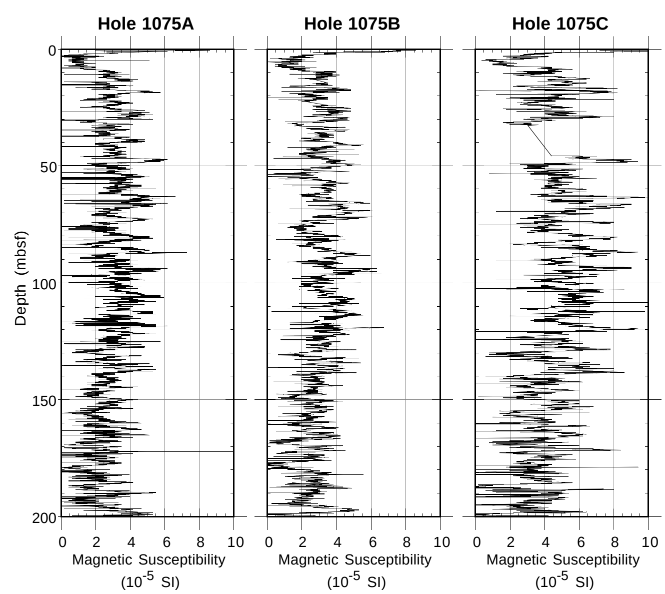


Figure 4. Magnetic susceptibility data for Site 1075 (from "Paleomagnetism" section, "Site 1075" chapter, this volume).

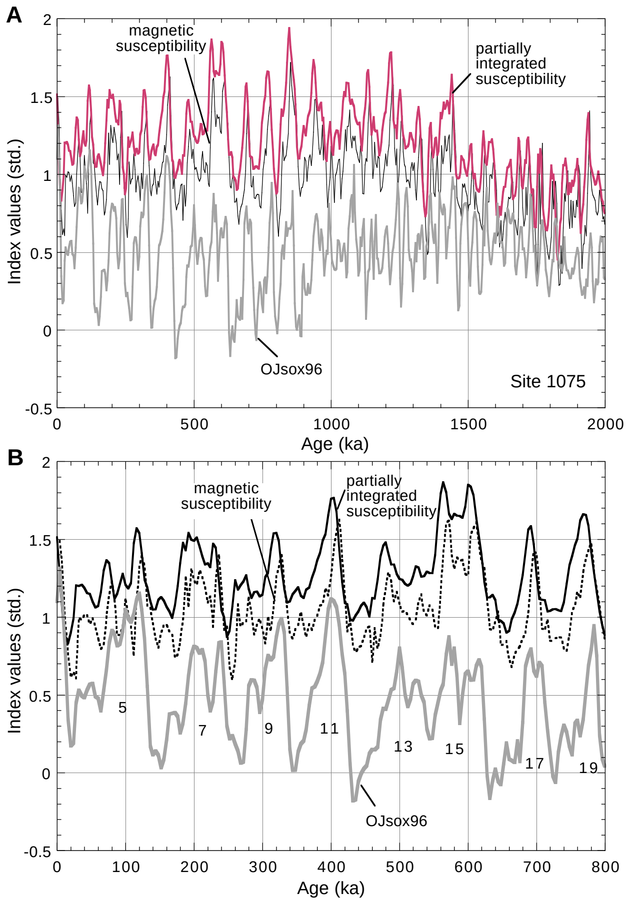


Figure 5. Match of magnetic susceptibility stack for Site 1075 to oxygen-isotope record of Ontong Java Plateau (OJsox96). The match is improved by partial integration of the magnetic susceptibility ("partially integrated susceptibility"). Isotope curve is from Berger et al. (1994); modified for last 800 k.y. in Berger et al. (1996). **A.** Last 2 m.y. **B**. Detail.

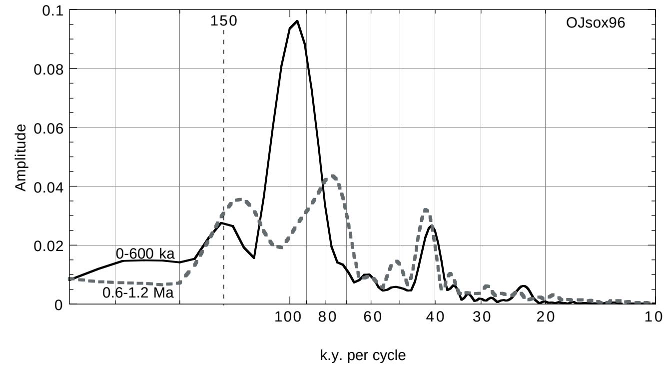


Figure 6. Spectrum of oxygen-isotope record from Ontong Java Plateau (OJsox96; Berger et al., 1994, 1996). Amplitude represents the Fourier components of the autocorrelation series. Note the absence of 100-k.y. power before the Milankovitch Chron (last 625 k.y.).

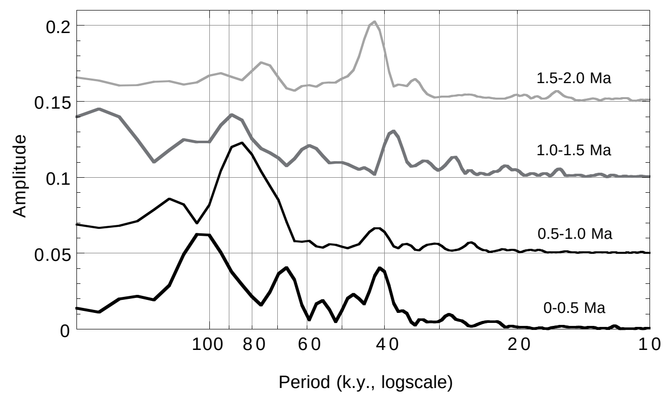


Figure 7. Spectrum of magnetic susceptibility for four intervals within the last 2 m.y. Age model from match to OJsox96 (see Fig. 5).

Quaternary and the sole one dominated by 100-k.y. climatic cycles. The detrended color data that have been stacked in the manner described for magnetic susceptibility are plotted in Figure 8. All values are standardized and offset for clarity.

It is obvious that the color cycles have much higher frequencies than those in the isotope curve, and that an influence of the ice-age cycles (100 and 41 k.y.) is not readily apparent (Fig. 8A). There is a hint of more reddish sediments being associated with the glacial stages. For the total reflectance, a similar relationship holds, except that high reflectance seems distinctly tied to interglacial conditions (Fig. 8B).

The overall negative correlation between color and reflectance within the 100-k.y. band holds true, especially for the Milankovitch Chron (Fig. 9A), but it tends to break down at times of minimum eccentricity of the Earth's orbit (near 400 and 800 k.y.). This points to the importance of eccentricity—or, rather, precession effects modulated by eccentricity—in the production of color cycles. The curve labeled "model" is the near-100-k.y. component of the ice-age template of Berger et al. (1995), which contains a saw-tooth oscillation feeding off precession. It is in phase with color and reflectance for the Milankovitch Chron, but not in the Croll Chron, showing that different rules of sedimentation govern the two periods.

The relationship of color and reflectance to changes in obliquity of the Earth's axis is strong only for the late Brunhes (last 350 k.y.), but not earlier (Fig. 9B). This suggests that climatic messages from the southern polar region became stronger at that time in the Congo Fan region. The change is reminiscent of the mid-Brunhes climatic shift observed by Jansen (1990), but it moves in the opposite sense. Interestingly, within the obliquity-related cycle, color and reflectance tend to be in a phase opposite to that in the 100-k.y. cycle. This strongly suggests that different sediment components determine color and reflectance within different spectral bandwidths. The curves labeled "model" and "obliquity" in Figure 9B are derived from the ice-age template of Berger et al. (1995) and from the orbital data of Berger and Loutre (1991), respectively.

In comparing the obliquity-related color cycles with orbital forcing, we are at the limit of what can be done with the present age model, which has an uncertainty in phase of about 10 k.y. It is moot, therefore, to discuss the phase of precessional cycles. However, we can study the overall pattern of the precessional forcing on the sedimentary cycles as expressed in color (Fig. 10). Precessional amplitudes in color and reflectance follow the amplitudes of orbital forcing in many respects. For example, we see large amplitudes around 100, 200, 600, 700, and 950 ka, as expected. However, the match is not good in some intervals. Perhaps the most striking mismatch is around 400 ka, where orbital forcing is subdued, and yet the response of the system is quite strong. This means that the sensitivity of the system changes perhaps as a function of conditions provided by the 100-k.y. oscillations.

It is apparent that the precessional amplitudes in the reflectance cycles are much weaker than those in the color cycles, especially within the Milankovitch Chron (Fig. 10). A plot of the pertinent spec-

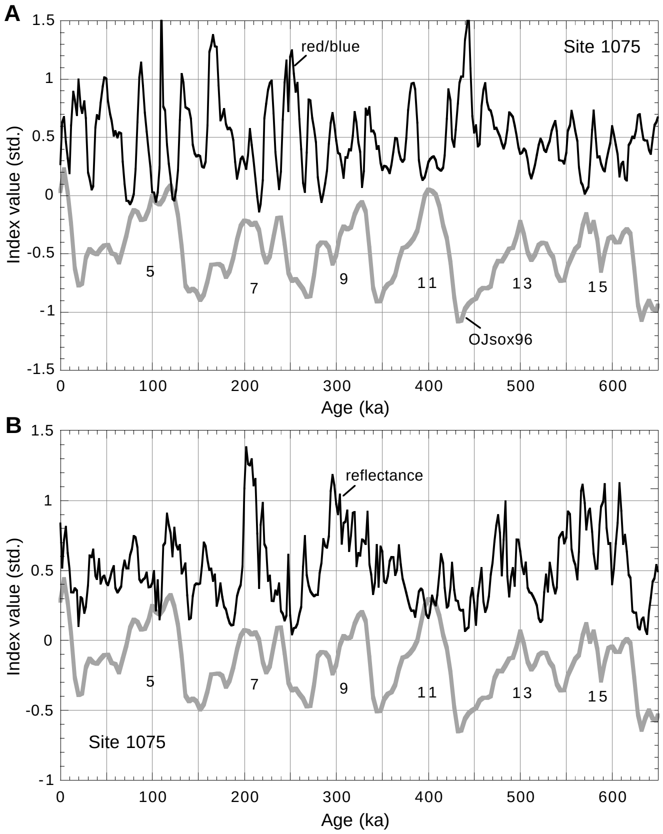


Figure 8. Age model for the stacked reflectancy series for the Milankovitch Chron. Gray curve = oxygen-isotope record OJsox96 (as in Fig. 5). **A.** Color (red/blue ratios). Note maxima coinciding with glacials. **B.** Reflectance (albedo). Note maxima coinciding with interglacials.

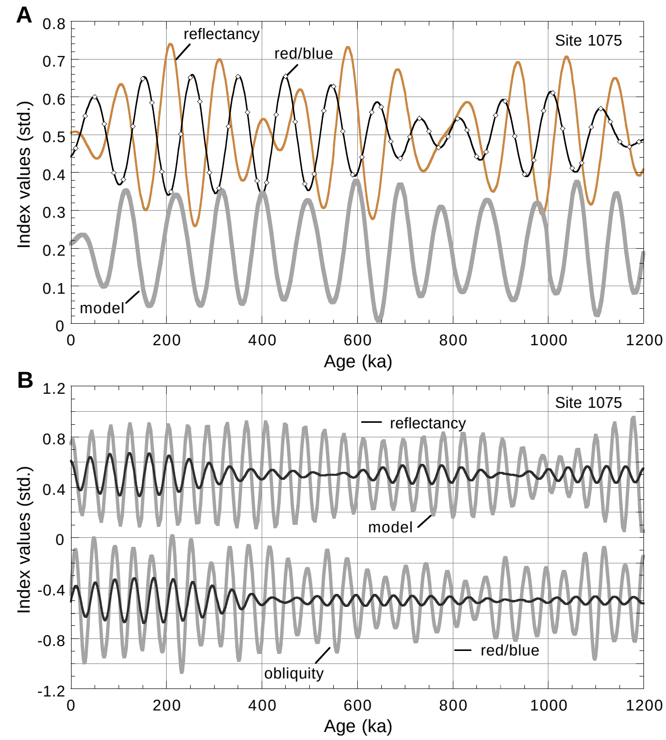


Figure 9. Filtered reflectancy series for the last 1.2 m.y. **A.** The 100-k.y. band (± 15%). **B.** The 41-k.y. band (±10%). The model is the equivalent band derived from filtering the Milankovitch template of Berger et al. (1995; i.e., sea level). Obliquity = actual values taken from Berger and Loutre (1991).

tra brings out the pattern more clearly (Fig. 11). The curves shown depict the amplitude of Fourier components of the autocorrelation series for each of the two color-related variables and for three different periods (0–400, 400–800, and 800–1200 ka). Outstanding features are the substantial power of the reflectance near 100 k.y. throughout the record and the impressive spike of power in the precessional band in the red/blue ratio for the last 400 k.y. Also of interest is the fact that in both variables, obliquity-related cycles are important only within the last 400 k.y., but not earlier. The offset in precessional power in the spectrum of both variables for the period from 0.8 to 1.2 Ma and from the position near 23 k.y. to one just below 20 k.y. suggests that the sedimentation rate was set too high (by ~10%), which would throw the age scale off by 40 k.y. at 1.2 Ma.

## DISCUSSION AND CONCLUSIONS

Color-related variables in the Quaternary sediments recovered from Site 1075 in the northern Congo Fan region show distinctive fluctuations, which reflect regional and global orbital forcing and local response of the depositional system. The color pattern (red/blue) seems less complex than the reflectance pattern (albedo). Color variation is dominated by precessional cycles, whereas reflectance has power in a larger number of competing cycles (Fig. 11). Also, total reflectance has a much stronger long-term trend than the red/blue ratio (compare Figs. 1 and 2).

The depositional system includes the sediment-producing drainage basin of the Congo River; the river transport; the redistribution processes, including possible intermediate storage on the shelf; and marine processes. The marine factors include productivity patterns of both the open ocean and the coastal ocean, as well as changing carbonate chemistry of deep waters. The production of sediment in the Congo Basin is largely a function of the wetness of the climate (Jansen, 1990). This factor should be strongly related to precession, which controls the intensity of monsoons (Rossignol-Strick, 1985; Schneider et al., 1997). Redistribution of sediment involves the position of sea level and is therefore co-determined by global ice volume. Ice volume varies with obliquity and eccentricity and also has its own oscillatory behavior, which gradually changes from the early to the late Quaternary (Berger et al., 1995).

Ocean productivity is a function of winds, which in the tropical Atlantic, depend on monsoonal amplitudes (McIntyre et al., 1989; Schneider et al., 1994, 1996; Wefer et al., 1996) and on the nutrient supply within the thermocline waters (Molfino and McIntyre, 1990; Hay and Brock, 1992; Herguera and Berger, 1994; Berger and Lange, 1997). Carbonate saturation of deep waters is a function of water age: the older the deep water, the less saturated it is. Whenever the influence of North Atlantic Deep Water (NADW) is strong (despite the limited access to the Angola Basin), carbonate saturation is elevated and carbonate preservation is enhanced. The production of NADW is a result of both evaporation and cooling of North Atlantic surface waters. Thus, NADW depends both on subtropical and high-latitude processes, and it should therefore carry both low-latitude (precessional) and high-latitude (obliquity- and ice-mass-related) cyclicities.

Against this background, it is clear that we will not be able to separate global from regional, high-latitude from low-latitude, and continental from oceanic influences in the color cycles based on spectral analysis alone. However, when this analysis is combined with calibration against the main components, much insight will be gained. The available data suggest that productivity variations are responsi-

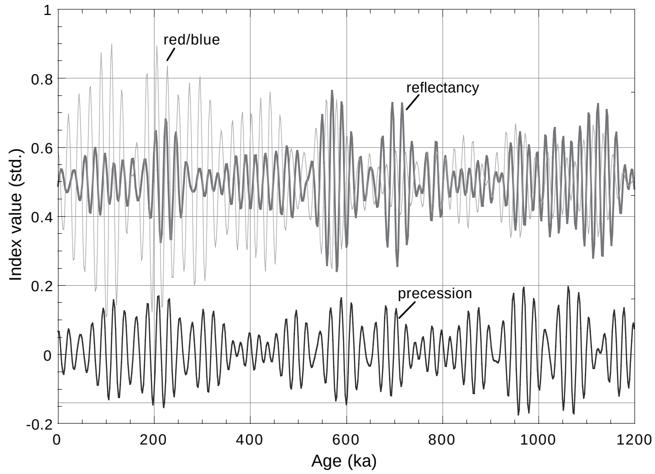


Figure 10. Filtered reflectancy series for the band between 17 and 25 k.y., shown for the last 1.2 m.y. Precession = variations in insolation resulting from long-term fluctuations in eccentricity and the changing perihel positions with respect to the northern solstice (taken from Berger and Loutre, 1991).

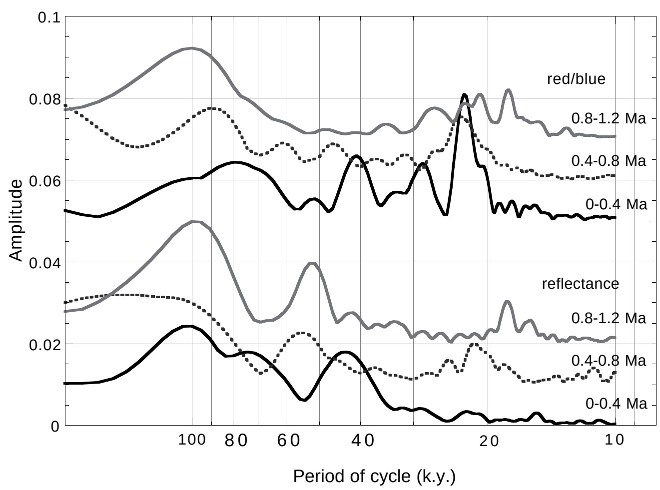


Figure 11. Spectra of color and total reflectance for three intervals within the last 1.2 m.y. Amplitude represents the Fourier components of the autocorrelation series.

ble mainly for the fluctuations in the red/blue ratio through the changing abundance of organic matter (Fig. 3). The strong negative correlation with sea level in the 100-k.y. band (Fig. 9A) suggests a greatly enhanced supply of organic matter during glacial periods, with a distinct shift toward red in the red/blue ratio. The same relationship is seen in the (assumed) phase with obliquity (Fig. 9B). There is a hint that the same phase holds with respect to precession (Fig. 10), with higher productivity when perihel occurs in northern winter.

The most important result is that the sensitivity of the depositional system, as reflected in color variation, changes through time. Indications are that the largest amplitudes in red/blue ratio occurred in the Milankovitch Chron (last 625 k.y.) in both precessional and obliquity-related bands. This interval is characterized by a dominant 100-k.y. oscillation in global ice mass. Apparently, the presence of extreme global conditions provide the overall framework for increased variability in sediment supply, both from land and the ocean. It is as though more power is available (e.g., from an increased planetary temperature gradient) to drive the subsystems to greater extremes as they obey the forcing from changing insolation patterns.

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**Ms 175IR-122**