# High- and Low-Latitude Climate Interactions: Evidence for Enhanced Aridity of Asian Monsoon Dust Source Areas After 2.4 MYR from ODP Leg 117 Magnetic Susceptibility Data

Peter deMenocal and Jan Bloemendal

**ABSTRACT:** Whole-core magnetic susceptibility can sometimes be used as a rapid and sensitive indicator of variations in the concentration of terrigenous material. We apply this approach to study the evolution of Plio-Pleistocene climatic cycles of terrigenous sedimentation at Ocean Drilling Program Site 721, on the Owen Ridge in the Arabian Sea. Aerosol and sediment studies have shown that terrigenous sedimentation on the Owen Ridge is dominated by variations in the supply of eolian dust borne by summer southwest monsoon winds. Terrigenous extraction analyses of the Site 721 sediments show that magnetic susceptibility is a conservative and sensitive tracer of the terrigenous (eolian) fraction variations at Site 721.

Spectral analysis of the susceptibility time series spanning the last 3.2 Myr show the record varies strongly at earth orbital periodicities. Prior to about 2.4 Myr, the record varies predominantly at the 23 and 19 kyr periodicities, corresponding to orbital precession; after 2.4 Myr it shows a significant increase in 41-kyr power corresponding to orbital obliquity. This shift coincides with the rapid expansion of Northern Hemisphere ice sheets at about 2.37 Myr. General circulation model experiments and paleoclimatological evidence from northeast Africa suggest the increase in 41-kyr power after 2.4 Myr may be reflecting periodic increases in monsoon dust source area aridity associated with the coeval expansion of Northern Hemisphere ice sheets, which varied predominantly at this periodicity.

## Introduction

Orbital perturbations that result from gravitational interactions with the moon and with the other planets give rise to cyclical variations of 100 kyr in Earth orbital eccentricity, 41 kyr in obliquity, and 23-19 kyr in precession (Berger 1978). These variations are climatically important, because they affect seasonal distribution of solar insolation received at any given latitude. Statistical analyses of the foraminiferal $\delta^{18}O$ record from deep-sea cores, which is largely a measure of glacial ice volume (Shackleton and Opdyke 1976), show that growth and decay of ice sheets have been strongly modulated by orbital insolation variations (Imbrie *et al.* 1984).

Similarly, other major components of climate, such as sea surface temperature, Asian and African monsoon intensity, deep circulation, and atmospheric $CO_2$, vary predominantly at orbital periodicities (Ruddiman and McIntyre 1984, Pokras and Mix 1985, Mix and Fairbanks 1985, Prell and Van Campo 1986, Raymo *et al.* 1989). However, measurement of conventional paleoclimatic indicators (*e.g.*, oxygen and carbon isotopes, carbonate, opal, and terrigenous fraction content) in deep-sea sediments is time consuming, so paleoclimatic indicators are needed that can be measured more rapidly.

Magnetic susceptibility is a measure of the concentration of magnetic material in a sample. It is not a remanence measurement; it is determined by the ratio of induced magnetization

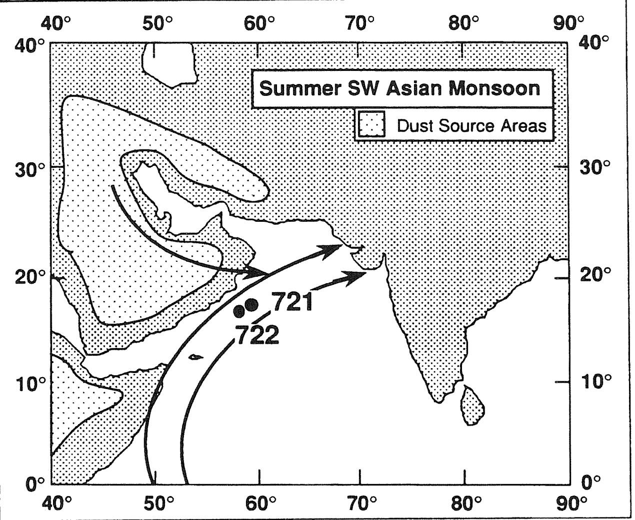
In: J.L. Betancourt and V.L. Tharp, editors. 1991. *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990*. California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

to an applied field and reflects the integrated contribution of all magnetic constituents. Since the terrigenous fraction of most deep-sea sediments contains trace amounts (typically <0.01%) of strongly ferrimagnetic minerals (*e.g.*, magnetite), variations in magnetic susceptibility are usually monitoring variations in terrigenous concentration. Provided susceptibility is shown to be a conservative indicator of the terrigenous fraction, its link to paleoclimate is through climatically-controlled variations in the supply of terrigenous and biogenic components (Kent 1982, Robinson 1986, Doh *et al.* 1988, Bloemendal *et al.* 1988, Bloemendal and deMenocal 1989, deMenocal *et al.* In Press). It is this link between climate and sediment magnetism that is investigated here.

The major aim of Ocean Drilling Program Leg 117 in the Arabian Sea was to study the late Neogene evolution of the Asian monsoon. The origin and dynamics of the modern Asian monsoon are complex, but observational and theoretical studies have provided a general understanding of its larger scale features (Hastenrath 1985). Northern Hemisphere heating during summer develops an intense low pressure cell over the Tibetan Plateau, which enables regional cyclonic circulation to prevail from May to September (Hastenrath and Lamb 1979). In the northwest Arabian Sea, strong southwest winds parallel the Arabian coast, carrying eolian detritus from northeast Africa and Arabia to the Arabian Sea and bringing the monsoon rains to southern Asia (Figure 1). Intensity of the summer Asian monsoon has been tied to orographic effects of the Himalayan mountains and the Tibetan Plateau, which tend to enhance the convergence of moist convection and latent heat (Ramage 1965, Hahn and Manabe 1975).

Figure 1
LOCATIONS OF SITES 721 AND 722
ON THE OWEN RIDGE,
IN THE WESTERN ARABIAN SEA

Lower tropospheric (1-2 km altitude) wind fields over the Arabian Sea during the summer monsoon (after Hastenrath and Lamb 1980) are shown by solid lines. Eolian dust source areas are based on satellite imagery from Sirocko and Sarnthein (1989).



Both general circulation model (GCM) experiments (Kutzbach 1981, Prell and Kutzbach 1987) and analyses of eolian and biogenic components in deep-sea cores (Pokras and Mix 1985, Prell and Van Campo 1986, Prell and Kutzbach 1987) have shown that seasonal insolation variations resulting from orbital precession have modulated the intensity of the Asian and African monsoons. Precession affects low-latitude summer insolation at periodicities of 23 and 19 kyr (Berger 1978); maximum summer insolation is achieved when the summer solstice coincides with perihelion (*e.g.*, 11 Kyr BP), and paleoclimatic data have shown that the African and Asian monsoon systems were intensified at these times (Pokras and Mix 1985, Prell and Van Campo 1986, Clemens and Prell 1990).

## Methods, Time-Control, and Power Spectral Analysis

Site 721 is in 2028-meter-deep water near the crest of the Owen Ridge in the Arabian Sea and rises 2000 meters above the surrounding bathymetry. Satellite imagery (Sirocko and Sarnthein 1987) and sediment core studies (Sirocko and Sarnthein 1987, Clemens and Prell 1990) show that terrigenous sedimentation in the Arabian Sea is dominantly eolian. Volume magnetic susceptibility was measured on whole core sections at 5-centimeter intervals using a pass-through sensor. Three holes were drilled at Site 721 (A, B, and C), and between-hole correlations using the susceptibility data were used to construct complete composite sequences (deMenocal *et al.* In Press) (Figure 2).

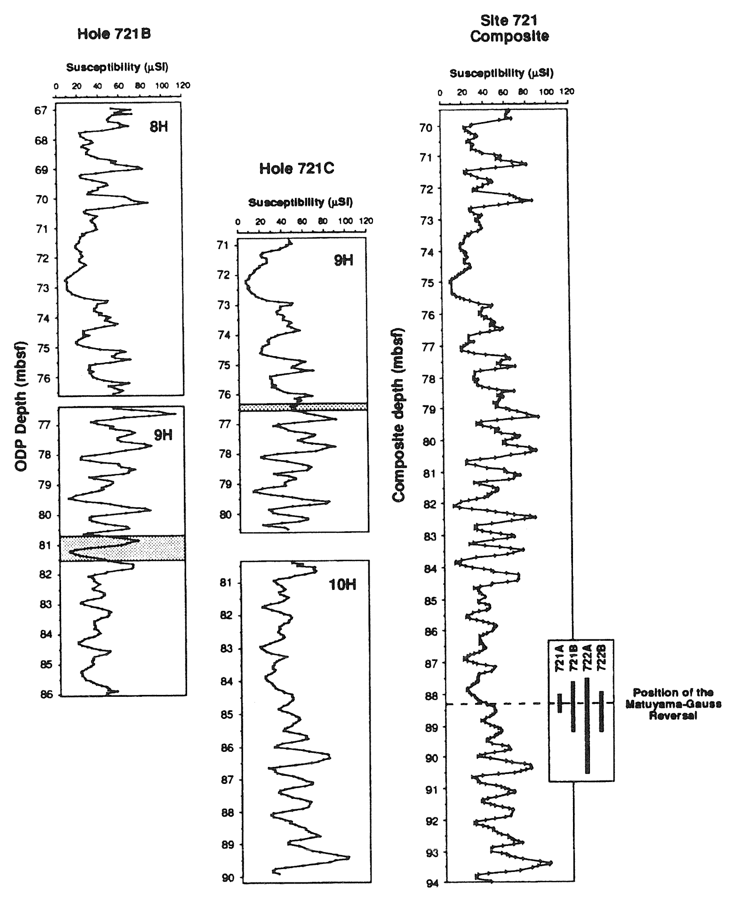
Age models were constructed using bio- and magnetostratigraphic datums. Mean sedimentation rate determined from these data is ~3.5 cm/kyr. Oxygen isotope data (Clemens and Prell In Prep.) were used to establish age/depth relationships for the interval 0-1 Myr. The final age model included as many datums as possible within a series of straight-line segments. The Site 721 magnetic susceptibility time series is shown in Figure 3. The time series was divided into overlapping 0.4-Myr intervals, and spectral analysis was performed on each interval using the Blackman-Tukey method (Imbrie *et al.* 1984).

The 0.4-Myr-interval power spectra results, shown in Figure 4, indicate a shift in spectral character at about 2.4 Myr. Before 2.4 Myr, the data vary predominantly at the 23 and 19 kyr precessional periodicities. The variance associated with this precession component significantly exceeds that associated with obliquity for all intervals before 2.4 Myr. After 2.4 Myr, there is a significant increase in variance at the 41-kyr periodicity and a corresponding reduction in variance at the 23-kyr and 19-kyr periodicities. The increased variance at the 41-kyr periodicity persists over the entire 0-2.4 Myr interval.

To examine coherency between the orbitally-driven insolation variations *(the forcing)* and the susceptibility variations *(the response)*, the susceptibility time series were filtered using a bandpass filter centered at 22 kyr, corresponding to orbital precession. The extracted component was then correlated *(tuned)* to the calculated precession curve using an inverse correlation method (Imbrie *et al.* 1984, Martinson *et al.* 1982). The filtered susceptibility data at Site 721 exhibit the modulated character of the precessional curve (Figure 5). Coherency is 0.84 over the 3.2-1.6 Myr interval and is even higher (0.89) from 3.2-2.4 Myr. Although the tuning procedure maximizes correlation between the two signals, the coherency of the 400-kyr and 100-kyr modulation envelopes is a real component of the susceptibility data. These results show the strong orbital control of the Site 721 susceptibility record and a shift from strong precessional forcing before and strong obliquity forcing after about 2.4 Myr. This raises the questions of what aspect(s) of the relevant climate systems does the susceptibility record reflect, and what is the significance of the periodicity shift at 2.4 Myr?

## Figure 2
## INTER-HOLE CORRELATIONS USING THE MAGNETIC SUSCEPTIBILITY DATA, SITE 721

Shaded areas represent sections missing between core breaks; these were used to construct a composite sequence, a portion of which is shown to the right. The susceptibility data were also used to constrain the position of the Matuyama-Gauss Chronozone boundary (2.47 Myr; at 88.30 mbsf composite depth.



## Figure 3
## MAGNETIC SUSCEPTIBILITY TIME-SERIES, SITE 721

Age control from 0-1 Myr was based on $\delta^{18}O$ stratigraphy (Clemens and Prell In Press).
Age control from 3.2-1.0 Myr was based on bio- and magnetostratigraphic datums.

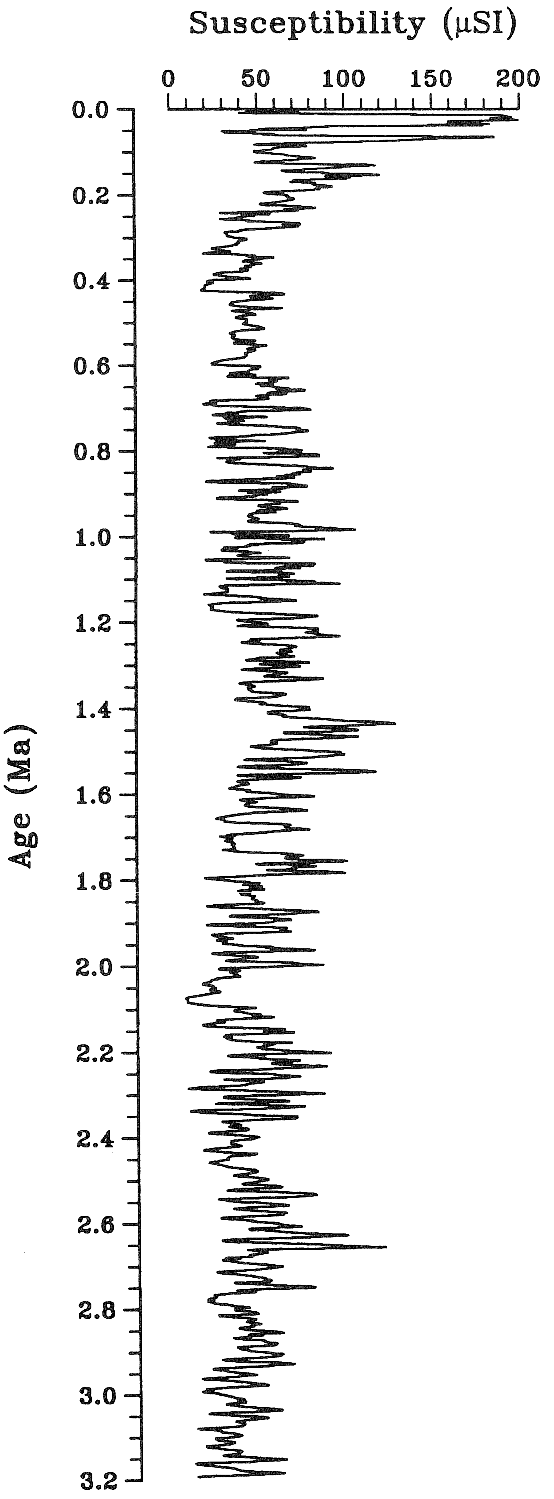
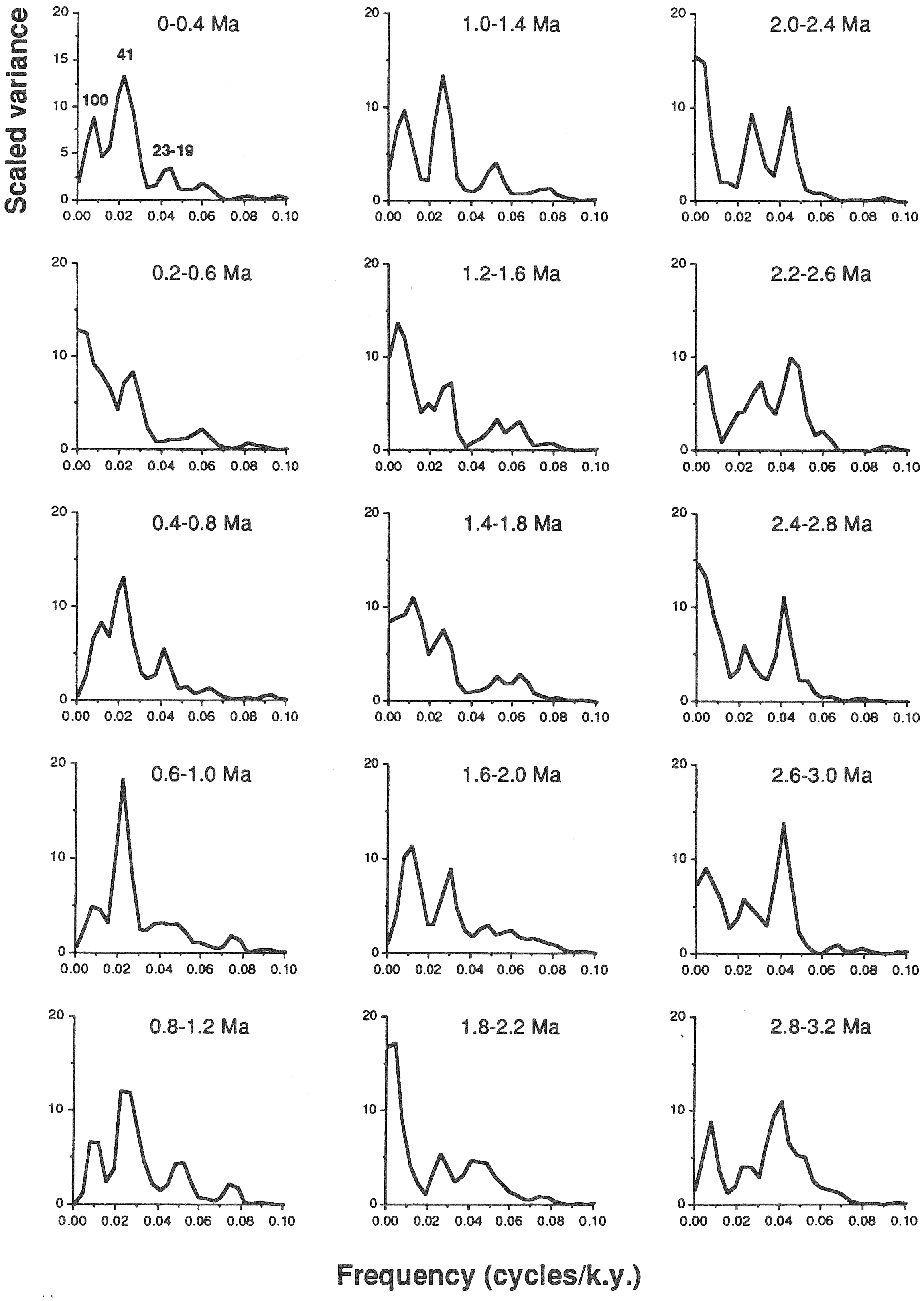


Figure 4

POWER SPECTRA CALCULATED FOR OVERLAPPING 400-KYR SEGMENTS OF THE SUSCEPTIBILITY TIME SERIES

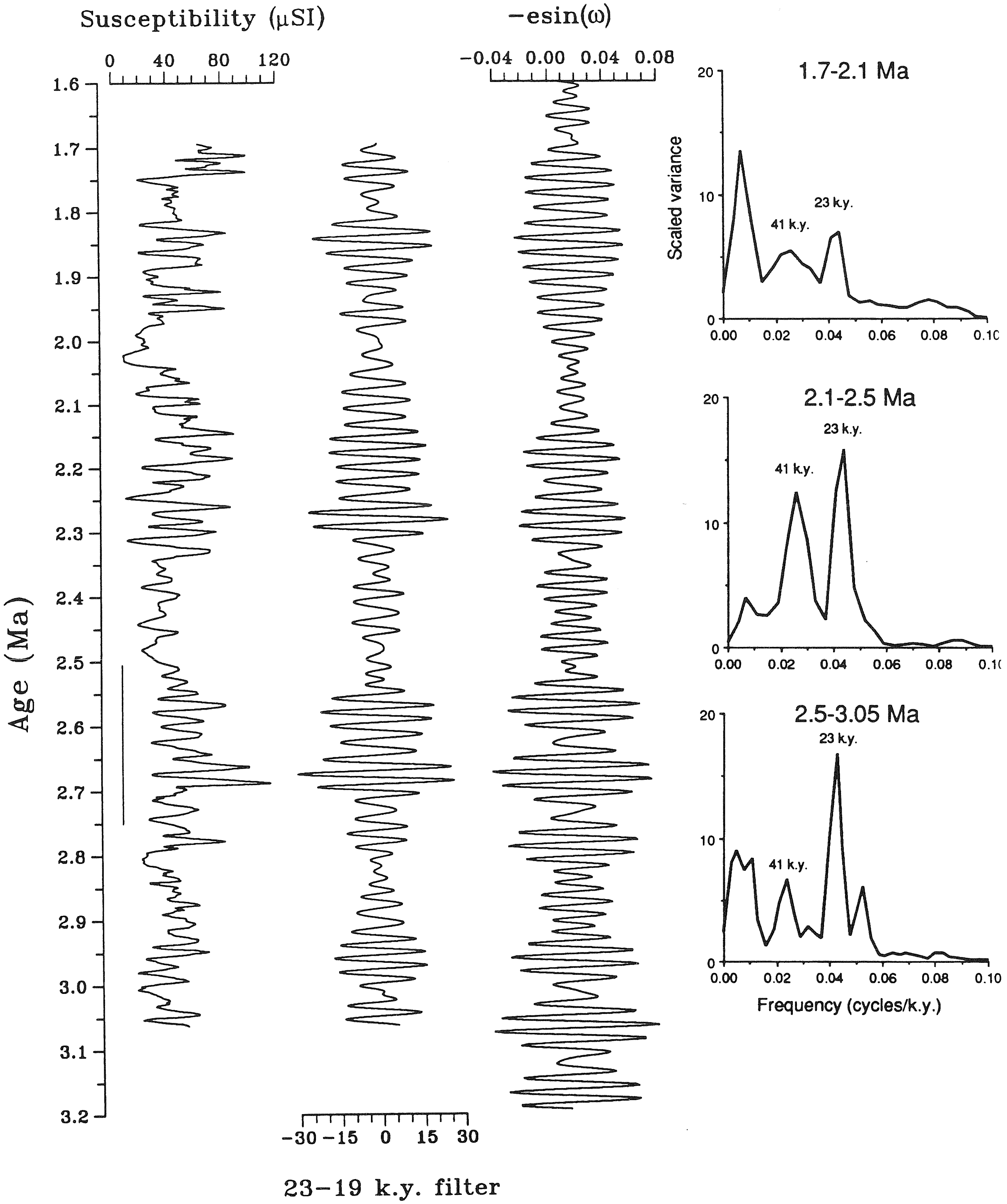
Data are shown as scaled variance. Note the increase in 41-kyr power after about 2.4 Myr.



## Figure 5

## CALCULATED PRECESSION (–esin(*w*)), 22-KYR BANDPASS FILTER OF THE SUSCEPTIBILITY RECORD, AND RAW SUSCEPTIBILITY RECORD FOR THE 3.2-1.6 MYR INTERVAL, SITE 721

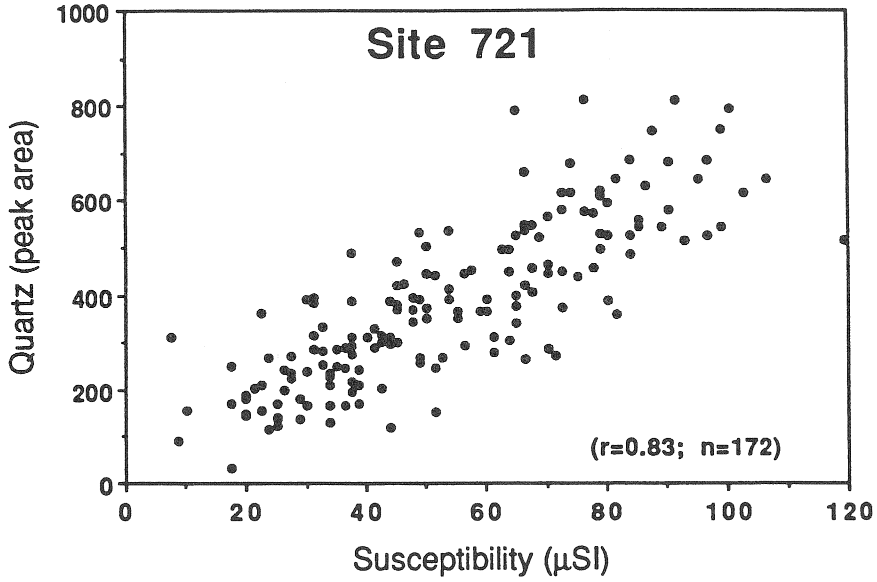
The filtered susceptibility data were correlated (phase-locked) to precision using a signal correlation package (Martinson et al. 1984) to demonstrate the degree of coherency between the presumed isolation forcing (–esin(w)) and the climate response (susceptibility). Coherency is highest (0.89) between precession and the filtered susceptibility over the 3.2-2.5 Myr interval; coherency of the entire 3.2-1.6 Myr interval is 0.86. The vertical line to the left shows the interval selected for the flux calculations.



## Climatic Origin of the Susceptibility Variations

Terrigenous extraction following procedures of Clemens and Prell (1990) was conducted on 94 samples from Site 721 (deMenocal *et al.* In Press). Samples were subjected to sequential chemical extractions of biogenic carbonate, opal, and organic carbon to isolate the mineral (eolian) fraction. The strong correlation between susceptibility and terrigenous percent (r=0.98) shows susceptibility is an accurate proxy indicator of terrigenous content. Figure 6 shows the advantage of using susceptibility; the terrigenous extraction analyses required about 2 hours per sample, whereas magnetic susceptibility was measured in 10 seconds on whole, unsplit cores.

Figure 6
CORRELATIONS BETWEEN MAGNETIC SUSCEPTIBILITY AND QUARTZ ABUNDANCE



Results of bulk sample X-ray diffraction analyses are shown in Figure 7. The strong correlation between susceptibility and quartz (r=0.83) reflects the eolian origin of the terrigenous fraction variations. There is also a strong positive correlation between susceptibility and dolomite (r=0.70). Aerosol studies have shown that quartz (and dolomite) are dominant constituents of summer monsoon dust (Stewart *et al.* 1965, Goldberg and Griffin 1970, Kolla and Biscaye 1977, Sirocko and Sarnthein 1989, Nair *et al.* 1989).

Using the "tuned" Site 721 susceptibility record to generate detailed age/depth relationships for a short interval between 2.7 and 2.5 Myr and available dry bulk density data, we converted the terrigenous concentrations to terrigenous accumulation rates. Figure 8 shows the strong positive correlation between susceptibility and terrigenous accumulation rate. These data indicate that susceptibility variations are reflecting variations in terrigenous supply rather biogenic dilution; the correlation between susceptibility and biogenic accumulation rate was poor. A study of late Pleistocene terrigenous accumulation on the Owen Ridge by Clemens and Prell (1990) supports this conclusion.

The strong correlation between susceptibility and the concentration and accumulation rate of terrigenous sediment, and the occurrence within this fraction of minerals indicative of an eolian source, leads us to conclude that the Site 721 susceptibility record is a direct expression of variations in the eolian supply of terrigenous material by the Asian monsoon.

Figure 7

CORRELATIONS BETWEEN MAGNETIC SUSCEPTIBILITY AND TERRIGENOUS PERCENT

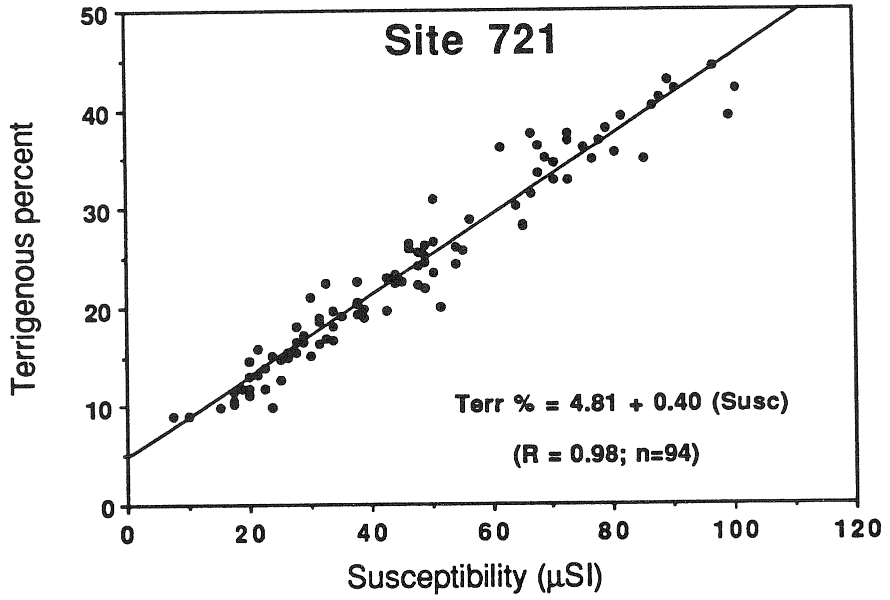
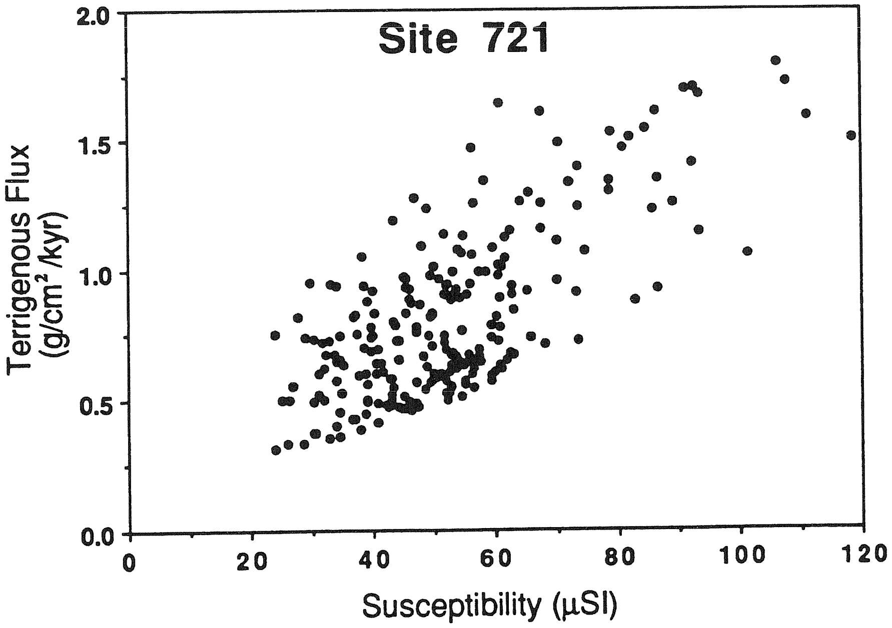


Figure 8

CORELATIONS BETWEEN MAGNETIC SUSCEPTIBILITY AND TERRIGENOUS ACCUMULATION RATE



## Origin of the 2.4-Myr Shift in Variance

The predominance of 23 and 19 kyr variance in the susceptibility records prior to 2.4 Myr suggests that terrigenous deposition from the Asian summer monsoons was largely modulated by summer insolation variations due to precession. Atmospheric GCM experiments have shown that, in the absence of other factors, monsoonal circulation is extremely responsive to precessional variations in local summer insolation and that the response is approximately linear (Prell and Kutzbach 1987). We interpret the strong precessional-band susceptibility variance prior to 2.4 Myr to reflect predominance of insolation-driven variations in summer monsoon intensity or source area aridity.

The marked increase in variance at the 41 kyr periodicity after about 2.4 Myr coincides with initiation of major Northern Hemisphere glaciation (Shackleton *et al.* 1984), and GCM results and geological evidence suggest this may reflect ice sheet effects on source areas of monsoon dust in northeast Africa and Arabia. The increase in power at 41 kyr is particularly significant, because the late Pliocene marine $\delta^{18}O$ record varies almost purely at this periodicity (Ruddiman *et al.* 1989, Raymo *et al.* 1989).

General circulation model experiments have suggested that northeastern Africa and Arabia may have experienced enhanced aridification when ice sheets were more extensive than today. Experiments with the GISS II GCM show that inclusion of LGM ice alone causes dramatic cooling (–5 to –10°C) and significant rainfall decreases (1-2 mm/day) over northeastern Africa, Arabia, and Mesopotamia during winter (Rind 1987, deMenocal and Rind In Prep.). This is apparently a direct effect of the downstream advection of cooler and drier air from the high-latitude Fennoscandian ice sheets. These results suggest that monsoon dust source areas are subject to enhanced aridification during times of increased high-latitude ice sheet cover. Late Pleistocene paleoclimate data from this region and the adjacent Arabian Sea support this relationship (Kolla and Biscaye 1977, Van Campo *et al.* 1982, Clemens and Prell 1990, Bonnefille *et al.* 1990).

Terrestrial paleoclimate data from northeastern Africa support a transition to a regionally cooler and drier climate at about 2.4 Myr. The strongest evidence for east African cooling and drying at 2.4 Ma is based on palynological data from diatomite sediments at Gadeb (Ethiopian Highlands), where a vegetation descent of at least 1-1.5 km has been shown to occur at some point between two radiometrically-dated tuff layers at 2.51 Myr and 2.35 Myr (Bonnefille 1983). The Gadeb pollen data (at 2300 msl) show an abundance of shrub, heath, and grass (largely *Ericaceae* and *Gramineae*) pollen types, which today are found only in the cooler montane climate above about 3500 msl. The temperature decrease is equivalent to about 4-6°C (Bonnefille 1983).

This shift to regionally cooler and drier conditions at about 2.4 Myr is also supported by pollen data from lower Omo, near Lake Turkana, where there is a coeval expansion of savanna grasslands (Bonnefille 1976). Bonnefille and Letouzey (1976) have shown that fossil wood and fruits with rain forest affinities disappeared from the lower Omo region at about this time. Abell (1982) and Cerling *et al.* (1977) have presented stable isotopic evidence from Lake Turkana gastropods and pedogenic carbonate horizons that also support a trend toward reduced precipitation between two radiometrically dated tuffs at 3.2 Myr and 1.9 Myr.

## Acknowledgments

We thank the members of the shipboard scientific and technical party of Leg 117 for their help in performing the whole-core susceptibility measurements and the X-ray diffraction mineralogy. We thank Rebecca Esmay and Bettina Domeyer for their assistance in the terrigenous extraction and XRD laboratory work. Computing facilities were provided by the Borehole Research Group. W. Ruddiman, J. King, S. Clemens, and D. Murray provided constructive comments.

This research was supported by funding from USSAC and by National Science Foundation grant OCE-89-11206.

## References

Abell, P.I. 1982. "Paleoclimates at Lake Turkana, Kenya, from Oxygen Isotope Ratios of Gastropod Shells". *Nature* 297:321-323.

Berger, A.L. 1978. "Long-Term Variations of Caloric Solar Insolation Resulting from Earth's Orbital Variations". *Quat. Res.* 9:139-167.

Bloemendal, J., and P. deMenocal. 1989. "Evidence for a Shift in the Climatic Variability of the African and Asian Monsoons at 2.5 Ma: An Application of Whole-Core Magnetic Susceptibility Measurements to Paleoclimatology". *Nature* 342:897-899.

Bloemendal, J., B. Lamb, and J. King. 1988. "Paleoenvironmental Implications of Rock-Magnetic Properties of Late Quaternary Sediment Cores from the Eastern Equatorial Atlantic". *Paleoceanography* 3:61-87.

Bonnefille, R. 1983. "Evidence for a Cooler and Drier Climate in the Ethiopian Uplands, 2.5 Ma Ago". *Nature* 303:487-491.

_______. 1976. "Palynological Evidence for an Important Change in the Vegetation of the Omo Basin Between 2.5 and 2.0 Ma". In *Earliest Man and Environments in the Lake Rudolf Basin.* Ed. Y. Coppens *et al.* Univ. of Chicago Press. pp.421-431

Bonnefille, R., J.C. Roeland, and J. Guiot. 1990. "Temperature and Rainfall Estimates for the Past 40,000 Years in Equatorial Africa". *Nature* 346:347-349.

Bonnefille, R., and R. Letouzey. 1976. "Fruits Fossiles D'Antrocaryon Dans la Vallée de l'Omo (Éthiopie)". *Adansonia* 16:65-82.

Cerling, T.E, R.L. Hay, J.R. O'Neil. 1977. "Isotopic Evidence for Dramatic Climate Changes in East Africa During the Pleistocene". *Nature* 267:137-138.

Clemens, S., and W. Prell. 1990. "Late Pleistocene Variability of Arabian Sea Summer-Monsoon Winds and Dust Source Aridity: An Eolian Record from the Lithogenic Component of Deep-Sea Sediments". *Paleoceanography* 5:109-146.

deMenocal, P.B. J. Bloemendal, and J.W. King. In Press. "A Rock-Magnetic Record of Monsoonal Dust Deposition to the Arabian Sea: Evidence for a Shift in the Mode of Deposition at 2.4 Ma". In *Scientific Rep. of the ODP 117, Part B.*

deMenocal, P. and D. Rind. In Prep. "Effects of Insolation, Ice Cover and Orography on the Winter and Summer Asian Monsoon: Results from the GISS II General Circulation Model". To be submitted to *J. Atmos. Sci.*

Doh, S-J., J. King, and M. Lienen. 1988. "A Rock-Magnetic Study of GPC-3 from the Central North Pacific and Its Paleoceanographic Implications". *Paleoceanography* 3(1):89-112.

Goldberg, E.D., and J.J. Griffin. 1970. "The Sediments of the Northern Indian Ocean". *Deep-Sea Res.* 17:513-537.

Hahn, D.G., and S. Manabe. 1975. "The Role of Mountains in the South Asian Monsoon Circulation". *J. Atmos. Sci.* 32:1515-1541.

Hastenrath, S. 1985. *Climate and the Circulation of the Tropics*, Boston, D.Reidel Publ.

Hastenrath, S., and P.J. Lamb, P.J. 1979. *Climate Atlas of the Indian Ocean. Surface Climate and Atmospheric Circulation*, Part I. Madison, WI, University of Wisconsin Press.

Imbrie, J., N.J. Shackleton, N.G. Pisias, J.J. Morley, W.L. Prell, D.G. Martinson, J.D. Hays, A. McIntyre, and A.C. Mix. 1984. "The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine O-18 Record". In *Milankovitch and Climate*, Vol. 2. Ed. A.L. Berger *et al.* Hingham, MA, D. Reidel Publ. pp.269-305.

Kent, D.V. 1982. "Apparent Correlation of Paleomagnetic Intensity and Climatic Records in Deep-Sea Sediments". *Nature* 299:538-539.

Kolla, V. and P. Biscaye. 1977. "Distribution and Origin of Quartz in the Sediments of the Indian Ocean". *J. Sediment. Petrol.* 47:642-649.

Kutzbach, J.E. 1981. "Monsoon Climate of the Early Holocene: Climate Experiment with the Earth's Orbital Parameters for 9,000 Years Ago". *Science* 214:59-61.

Martinson, D.G., W. Menke, and A. Stoffa. 1984. "An Inverse Approach to Signal Correlation". *J. Geophys. Res.* 87:4807-4818.

Mix, A.C., and R.G. Fairbanks. 1985. "North Atlantic Surface-Ocean Control of Pleistocene Deep-Ocean Circulation". *Earth and Planet. Sci. Lett.* 73:231-243.

Nair, R.R., V. Ittekkot, S.J. Manganini, V. Ramaswamy, B. Haake, E.T. Degens, B.N. Desai, and S. Honjo. 1989. "Increased Particle Flux to the Deep Ocean Related to Monsoons". *Nature* 338:749-751.

Pokras, E.M., and A.C. Mix. 1985. "Eolian Evidence for Spatial Variability of Late Quaternary Climates in Tropical Africa". *Quat. Res.* 24:137-149.

Prell, W.L., and J.E. Kutzbach. 1987. "Monsoon Variability Over the Past 150,000 Years". *J. Geophys. Res.* 92:8411-8525.

Prell, W.L., and E. Van Campo. 1986. "Coherent Response of Arabian Sea Upwelling and Pollen Transport to Late Quaternary Monsoonal Winds". *Nature* 323:526-528.

Ramage, C.S. 1965. "The Summer Atmospheric Circulation Over the Arabian Sea". *J. Atmos. Sci.* 23:144.

Raymo, M.E., W.F. Ruddiman, J. Backman, B. Clement, and D.G. Martinson. 1989. "Late Pliocene Variation in Northern Hemisphere Ice Sheets and North Atlantic Deep Water Circulation". *Paleoceanography* 4:413-446.

Rind, D. 1987. "Components of the Ice Age Circulation". *J. Geophys. Res.* 92:4241-4281.

Robinson, S.G. 1986. "The Late Pleistocene Record of North Atlantic Deep-Sea Sediments Revealed by Mineral-Magnetic Measurements". *Phys. Earth Planet. Inter.* 42:22-47.

Ruddiman, W.F., and A. McIntyre. 1984. "Ice-Age Thermal Response and Climatic Role of the Surface Atlantic Ocean, 40°N to 63°N". *Geol. Soc. Amer. Bull.* 95:381-396.

Ruddiman W.F., M.E. Raymo, D.G. Martinson, B. Clement, and J. Backman. 1989. "Pleistocene Evolution: Northern Hemisphere Ice Sheets and the North Atlantic Ocean". *Paleoceanography* 4:353-412.

Shackleton, N.J., *et al.* 1984. "Oxygen Isotope Calibration of the Onset of Ice-Rafting and History of Glaciation in the North Atlantic Region". *Nature* 307:620-623.

Shackleton, N.J., and N. Opdyke. 1976. "Oxygen Isotope and Paleomagnetic Stratigraphy of Pacific Core V28-239 Late Pliocene to Latest Pliocene". In *Investigations of Late Quaternary Paleoceanogrphy and Paleoclimatology.* Ed. R.M. Cline and J.D. Hays. Geol. Soc. Amer. Mem. 145:449-464.

Sirocko, F., and M. Sarnthein. 1989. "Wind-Borne Deposits in the Northwestern Indian Ocean: Record of Holocene Sediments versus Modern Satellite Data". In *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport.* Ed. M. Leinen and M. Sarnthein. Kluwer Academic Publishers. pp.401-433.

Stewart, R., O. Pilkey, and B.W. Nelson. 1965. "Sediments of the Northern Arabian Sea". *Marine Geol.* 3:411-427.

Van Campo, E., J.C. Duplessy, and M. Rossignol-Strick. 1982. "Climatic Conditions Deduced from a 150-KY Oxygen Isotope-Pollen Record from the Arabian Sea". *Nature* 296:56-59.