THE PALEOCLIMATIC RECORD PROVIDED BY EOLIAN DEPOSITION IN THE DEEP SEA:
THE GEOLOGIC HISTORY OF WIND

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Abstract. The mineral component of pelagic sediment is brought to the deep sea by transport in the wind. Extraction and analysis of this dust allows estimation of the past aridity of the eolian source region, via flux determinations, and of the intensity of the transporting winds, from grain size data. These two parameters, the grain size and mass flux of dust, vary independently. There are three significant sources of modern dust, eastern and central Asia, northwest Africa, and Arabia, all in the northern hemisphere. As the rainfall associated with the Intertropical Convergence Zone is an effective barrier to southerly transport of dust, the northern hemisphere is an order of magnitude more "dusty" than is the southern, an asymmetry that has characterized most of the Cenozoic. Eolian flux data show that most of the northern hemisphere was more arid during glacial maxima, with 3 to 5 times as much dust transported during glacial stages than during interglacials; only northwestern South America varied in the opposite sense. The periodicity of Quaternary variation in both eolian flux and eolian grain size data is strongly influenced by the Milankovitch cycles of orbital variability. Wind intensities vary on a shorter time scale than the general 100-kyr cycles of glaciation and general aridity. Eolian grain sizes display forcing at precessional (19 and 23 kyr), tilt (41 kyr), and at approximately 30 kyr periodicities. As a result the generalization that winds are uniformly stronger during glacial times is not valid. Whole-Cenozoic records show that the largest change in dust flux, an order of magnitude increase, occurred in the northern hemisphere and reflects continental drying associated with the late Pliocene onset of northern hemisphere glaciation. Southern hemisphere eolian records show no sign of paleoclimatic changes in the late Pliocene. The most important change in Cenozoic atmospheric circulation was a severalfold reduction in wind intensity that occurred at the time of the Paleocene-Eocene boundary. Before then, latest Cretaceous and Paleocene winds were essentially as strong as those of the late Cenozoic. This shift appears to be one of several climatic responses to a change in the nature and amount of global heat transport at about 55 Ma.

INTRODUCTION

Global climate is controlled by the composition of the atmosphere and by those agencies that transport heat and moisture around the world, the ocean and the atmosphere. Past changes in the relative abundance of trace "greenhouse" gases in the atmosphere have been documented in air bubbles trapped in ice cores and linked to changes in global temperature. The field of paleoceanography, developed in the past 20 years, has similarly provided considerable information about the history of ocean circulation and the role that circulation has played in the establishment of past climatic regimes. The atmosphere is an equal partner with the oceans in questions of climatology; it transports the same amount of heat as the oceans and brings moisture to continents. The most direct proxy indicator of past atmospheric circulation is the mineral grains raised from the continents by dust storms and transported great distances to the ocean basins.

Although Darwin [1846] wrote a short paper about eolian dust and Maury [1855] devoted a chapter to it ("Red fogs and sea dust"), it was another century before marine scientists began to realize the importance of the eolian contribution to deep sea sediments. Two decades later in the 1970s, as a result of a rapidly growing body of research on the generation and transport of dust, a few workers began to realize the great potential of the dust record preserved in the deep sea as a proxy indicator of past continental climates and atmospheric transport processes. In the past 15 years, several groups have used this new understanding to develop eolian dust records of the geologic history of atmospheric circulation and continental climate [Leinen and Heath, 1981; Sarnthein et al., 1982; Rea et al., 1985a; Clemens and Prell, 1990].
Here I present what we know, think we know, and do not know about the eolian record in the deep sea. Because there are now a number of good summary articles available on modern processes of atmospheric transport of particulates, I will treat that aspect only briefly and refer the reader elsewhere for detailed information. The various problems and pitfalls with the sedimentology and interpretation of fine-grained pelagic sediments will be reviewed so that the general reader may gain some understanding of the validity of the records we generate. Finally, I will present an overview of the results of the last 15 years of research on dust deposition in the deep sea, with a bit more emphasis on the paleoclimatic significance than on the various geochemical aspects of that process.

BACKGROUND

Earlier Investigations

Although scientists as early as Darwin [1846] suggested that the eolian transport process could be responsible for important mineral deposits in the deep sea, during the first half of this century only a few remarked on the eolian process, commenting mostly on dusts downwind from the Sahara [Radcweski, 1939]. Kuenen [1950], in the first marine geology textbook published after World War II, noted the importance of Saharan dust in sediments of the northern subtropical Atlantic. A similar recognition came for the North Pacific in the late 1950s when Rex and Goldberg [1958] correlated the latitudinal band of quartz-rich sediments at about 30°-40°N to the distribution of arid lands in Asia and to the zonal westerlies (see also Menard [1964]).

A general recognition of the importance of eolian deposition occurring started in the late 1950s and early 1960s [Rex and Goldberg, 1958; Griffin and Goldberg, 1963]. Windom [1969] studied the windborne material captured in remote mountain snows and extrapolated its importance for pelagic sediments; Heath [1969] was the first to recognize that continentally derived, atmospherically transported minerals were a primary component of pelagic sediments through much of the Tertiary, and Ferguson et al. [1970] first demonstrated the similarity between currently transported mineral aerosol and the mineralogy of the underlying sediment.

In the early 1970s there began a considerable amount of interest in dust and its transport process, and the atmospheric science community began to sample and trace dusts. Aerosol sampling was conducted by D. A. Gillette and coworkers [Gillette and Porch, 1970; Gillette, 1974], J. M. Prospero and coworkers [Prospero, 1968; Prospero and Bonatti, 1969; Prospero and Carlson, 1972], and many others with interests in the flux of chemical species to the ocean [e.g., Folger, 1970]. Sedimentological work with paleoclimatic implications was carried out by Parkin and colleagues [Parkin and Shackleton, 1973; Parkin, 1974; Parkin and Padgham, 1975], Jacobs and Hays [1972], and Jackson et al. [1973]. Lisitzin [1972] discussed the importance of eolian transport to the deep sea in his classic text. By 1975, Windom was confident that eolian dust made up over half of all the mineral component in pelagic sediments, and essentially all of the mineral component in the pelagic clays [Windom, 1975], an estimate confirmed many times over in the years since.

Modern Processes and Climatology

Dust storms and dust transport are seasonal, nearly all events occur in the spring. A single storm may dominate the annual flux of eolian minerals from land to sea. The pronounced seasonality in dust transport has been very well documented for the North Atlantic downwind from the Sahara [Prospero et al., 1970, 1981; Prospero and Nees, 1977, 1986], for the North Pacific downwind from Asia [Shaw, 1980; Duce et al., 1980; Darzi and Winchester, 1982; Parrington et al., 1983; Uematsu et al., 1983; Merrill et al., 1989] and for the northwestern Indian Ocean [McDonald, 1938; Prospero, 1981a; Khalaf and Al-Hashash, 1983; Khalaf et al., 1985; Nair et al., 1989; Sirocko and Sarnthein, 1989; Clemens and Prell, 1990; Sirocko et al., 1991]. Nearly 2 decades of satellite photography have allowed atmospheric scientists to delineate the transport paths of the dust storms [Windom and Chamberlain, 1978; Prospero, 1981a; Sarnthein et al., 1981; Merrill, 1989a, b; Merrill et al., 1989; Duce et al., 1991] so we are aware that dust from North Africa dominates the subtropical Atlantic north of the equator and that dust from Asia dominates the entire Pacific north of the Intertropical Convergence Zone (ITCZ). In the western Pacific the ITCZ is less of a barrier to the southerly transport of Asian dust [Merrill, 1989b]. There is a vast literature in the soil sciences pertaining to the generation of dust from semiarid and arid lands; useful summaries are presented by Gillette [1981], Middleton [1989], and Nickling and Gilles [1989]. The mineral aerosol is of mixed grain size as it is lifted from the land surface [Gillette et al., 1978, 1980], but both downwind sampling [Gillette et al., 1974; Johnson, 1976, 1979; Windom and Chamberlain, 1978; Nickling, 1983; Hobbs et al., 1985] and theoretical calculations [Windom, 1969; Jaenicke, 1979; Schutz, 1979; Schutz et al., 1981] indicate that with time and distance (1000–2000 km) the average size of the eolian grains becomes essentially constant at a diameter of a few micrometers. These small grains, often referred to as the ”background aerosol" [Prospero et al., 1983], whose size and thus tendency to settle is in equilibrium with the transporting winds, are transported long distances and generally are re-
moved from the atmosphere by both dryfall and wash-out processes [Windom, 1975].

The amount of material that is transported by dust storms is directly related to the climate of the eolian source region. There have been numerous studies linking quantity of dust and frequency of dust storms to the presence or absence of rainfall for Saharan and Sahelian Africa which shows significant variability on El Niño–Southern Oscillation (ENSO) to decadal time scales (Figure 1) [Nicholson, 1982, 1985; Goudie, 1983; Middleton, 1985; Prospero and Nees, 1986; Tucker et al., 1991]. There is a similar modern literature for China in addition to 3 millennia of historical records from that region [Zhang, 1983, 1985; Middleton, 1991]. China and sub-Saharan Africa are the two dominant source regions for atmospheric mineral aerosol; other semiarid regions exhibit the same relationship between rainfall and dust availability (see papers in books edited by Pèwè [1981] and by Leinen and Sarnthein [1989]).

There have been a number of useful reviews and summaries of the generation and transport of eolian dust. The reader is referred to books on desert dust [Morales, 1979; Pèwè, 1981]. Prospero has authored several excellent papers that summarize information on the transport of dust to the ocean [Prospero, 1981b; Prospero et al., 1983, 1989]. The book by Pye [1987] is the most extensive single compilation of information and references on the nature and processes relating to atmospheric dust. Leinen and Sarnthein [1989] offer a variety of papers on all aspects of dust generation, transport and deposition in the deep sea. Volume 10 of Chemical Oceanography [Riley et al., 1989] is devoted entirely to aerosol transport and deposition in the Pacific basin. Most recently, Duce et al. [1991] published an extensive review paper on the input of mineral and various chemical species to the world ocean.

Assumptions Underlying Paleoclimatic Interpretation

This large amount of information documenting the present climatic and meteorologic controls on the dust reaching the ocean results in three general understandings that we may apply to studies of the geologic record of this process. A fundamental premise is that the amount of dust generated from all but hyperarid regions is directly related to source area climate: the less rainfall, the more dust generated. In hyperarid environments, those areas with less than 100 mm of annual rainfall, dust generation falls off (Figure 2) [Goudie, 1983; Pye, 1989] because there is not enough moisture to break down the larger continental minerals, usually feldspars, into clays of a suitable size for long-distance transport. Under conditions of long-
Figure 3. Grain size of eolian dust extracted from North Pacific surficial sediment along a 4000-km longitudinal transect. The grain size reduction from 8.49μ to 8.70μ is equivalent to a reduction in particle diameter from 2.78 to 2.40 μm.

term stability, such hyperarid regions eventually are stripped of their fines, become deflated, and provide little further dust to the atmosphere. Present examples are the core desert regions of the Sahara, Australia, and southern Africa [Prospero, 1981b; Prospero et al., 1989]. For all but hyperarid regions therefore, we are safe in interpreting the mass accumulation rate or flux of eolian dust to the seafloor as an aridity signal: more dust reflects drier source regions.

A second basic assumption is that the size of the eolian grains in regions far from the source area is in equilibrium with the transporting winds (Figure 3) [Prospero et al., 1983; Janecek and Rea, 1985; Rea et al., 1985a] and therefore, as in other media, the grain size is a reflection of the energy of the transporting agent. Larger grains are interpreted as indicating stronger winds. This understanding has been utilized in three somewhat different ways by those studying the problem. The first size measurements on presumably eolian grains were made on quartz grains extracted from the bulk sediment by a rather laborious process [Oser, 1972; Dauphin, 1980]. Other workers have quantified the portion of the mineral component of deep-sea sediments coarser than some rather arbitrary diameter, usually between 6 and 8 μm [Parkin and Shackleton, 1973; Parkin, 1974; Sarnthein et al., 1982; Stein, 1985a, b]. At least part of the reason for examining only the coarser fraction is one of instrumental analysis: obtaining good, repeatable data on very small samples of micrometer-sized grains has been achievable only in the last 10 years or so. In our Pacific Ocean work we have used electronic particle size analyzers to conducted grain size analysis on the total mineral component [Rea et al., 1985a]. The size of the total eolian component, largely clay minerals, is smaller than that of the coeval quartz grains but shows the same downcore pattern of variability [Janecek and Rea, 1983]. Since roughly 95% of the eolian material in pelagic sediment cores is smaller than 6 or 8 μm, the size of the entire extracted eolian component is more representative of the transport processes than just the small percentage of coarse material. Whichever fraction is studied, the resulting grain size values are related to the energy of the transporting wind. Quantification of the relationship between size of grains and intensity of transporting wind has been attempted by Janecek and Rea [1985] on the basis of work of Gillette et al. [1974], and by Tsoar and Pye [1987]. Such a mathematical relationship is yet to be really well resolved, so interpretations remain semiquantitative at best.

Giant quartz grains, 50 to over 100 μm in diameter, have been observed in the atmosphere and in sediment traps downwind from Asia [Betzer et al., 1988] and in modern sediments downwind from the Sahara [Coude-Gaussen, 1989]. Because they settle out so quickly, it is theoretically not possible for sand-sized mineral grains to travel as much as 10,000 km in the wind. Their presence suggests an important deficit in our understanding of particulate transport mechanisms. Such grains are reportedly very rare in the subsurface sediment, but there have been few careful searches for them. Corliss and Hollister [1982] in their description of a pelagic clay core from the central North Pacific note the presence of large quartz grains throughout; to my knowledge, this is the only mention of such grains in a deep-sea core. I suspect that the giant grains are a reflection of the energetics of an individual dust storm. If so, the size difference between these grains and the background aerosol may provide an indication of "storminess" and these giant grains might provide a clue to "paleoweather" and the background mineral aerosol clues to paleoclimate, both from the same sample.

The third important lesson of the modern climatology of dust transport is that the amount of material transported to distal locations is not related to the average speed of the transporting zonal tropospheric winds (not to be confused with the strong winds of the individual dust storm). This is a particularly important point because such a presumed correlation has been a fundamental misunderstanding in much of the climate and paleoclimate community. On an annual basis, essentially all dust transport either from the Sahel to Barbados or from Asia to the North Pacific occurs in the spring, the time of decreasing zonal wind velocity, rather than in the winter when the trade winds and westerlies are much stronger. Six detailed data sets of eolian flux and grain size exist, each spanning the past several glacial-interglacial cycles (Figure 4): core RC11-210 from a distal setting in the equatorial Pacific Ocean over 6000 km from its South American source [Chuey et al., 1987]; Deep-Sea Drilling Project (DSDP)
hole 503B from the eastern equatorial Pacific [Rea et al., 1986], core V21-146 from the northwest Pacific 3650 km west of China [Hovan et al., 1989, 1991], core KK75-02 from the central North Pacific [Janecek and Rea, 1984, 1985], and core RC27-61 and Ocean Drilling Program (ODP) site 722 from a proximal setting just a few hundred kilometers off the Arabian desert in the northwestern Indian Ocean [Clemens and Prell, 1990, 1991b]. Data from these cores permit a clear demonstration of this independence of eolian grain size and mass accumulation rate (MAR). Figure 4 shows the dust flux values plotted against the grain size for these six cores and illustrates the distinct lack of correlation between dust fluxes and grain size.

The information relayed by the eolian grain size and eolian flux data are in some ways similar in concept to the competence and capacity of rivers: a transporting agent does not have to move particularly rapidly to move large amounts of material, but rapidly moving mountain rivers will transport very large grains. This false perception of a correlation between apparent wind speed and amount of material transported may have arisen because of a mistaken interpretation of hemipelagic cores as eolian (see below).

Some Sedimentology

Continently derived sediments arrive in the deep sea by a number of transport pathways. Coarser materials delivered to the edge of the continental shelf may accumulate to the point of instability and form powerful turbidity currents that move rapidly downslope. Deep-sea fans are constructed at the base of the continental slope in those regions where the supply rate of clastics is the dominant process [Normark et al., 1993]; where supply is relatively low or deep transport processes are more vigorous, these clastic contributions to the deep sea are smeared out along the lower part of the continental margin in the form of contourite and drift deposits. The relatively flat abyssal plains of the Atlantic basins, the Gulf of Alaska and Bering Sea, and the northern Indian Ocean are the result of turbidite deposition extending far out to sea. Most of the $1.5-2.0 \times 10^{16} \text{ g yr}^{-1}$ of sediment brought to the ocean in rivers is deposited on the continental
shelf or is transported offshore and eventually forms one of these sorts of deposits.

Icebergs calved from glaciers reaching the ocean carry poorly sorted sedimentary debris great distances. The most obvious of these materials are dropstones which occur in all high-latitude sediments during glacial times. Finer-grained materials are also ice rafted along with the pebbles, but at present there is little knowledge of the mass fluxes associated with this process. Turbidites, contourites, and most ice-rafted debris are all relatively easy to identify in either seismic reflection profiles or cores raised from the seafloor. Such sediments, once identified, are not used for eolian studies.

The significant sedimentary confusion to the eolian signal comes from hemipelagic sediments and processes. Hemipelagic deposits consist of fine-grained, silt- and clay-sized, muds deposited within hundreds of kilometers of the continental margin. These muds, derived from winnowing of continental shelf and upper slope sediments, move offshore within the water column at 2- or 3-km depth in a plume or cloud of limited vertical extent. Resulting deposits blanket continental slopes and regions of the seafloor adjacent to the continents. The horizontal advection of lithogenous material has been well documented by sediment trap studies. Traps situated 300 to 350 km west of northern California in a region of known hemipelagic deposition [Rea et al., 1985b] show increased accumulation of lithogenic components below about 2000- to 3000-m depth [Heath, 1983; Fischer et al., 1983]. Sediment traps from Manganese Nodule Project (MANOP) area H (for hemipelagic) in the eastern Pacific at 6.5øN, 93.0øW, roughly 900 km offshore, also show some increased accumulation of lithogenic materials at depth [Fischer, 1983]. S. Honjo and colleagues have reported on the results of sediment trap work in the Panama Basin about 450 km west of Central America [Honjo, 1982; Honjo et al., 1982]. They were able to document that the flux of lithogenic materials increases dramatically with depth. The lithogenic materials entering those traps are 90% smectite-bidellite that is derived from the volcanic terrain of Central America and is similar to the underlying and nearshore sediment. Most of this mineral must reach the trap site by lateral advection within the water column [Honjo et al., 1982]. The lithogenic flux in the deep traps at the Panama Basin site is of the order of 1800 mg (cm² kyr)⁻¹ [Honjo et al., 1982]. The accumulation of more lithogenous material in deeper sediment traps than shallower ones at locations up to 500 km offshore, a strong indication of ongoing hemipelagic processes, is a common occurrence in the North Atlantic [cf. Heggie et al., 1987] and has been demonstrated recently in the northwest Pacific [Saito et al., 1992].

Hemipelagic sediment, on an individual sample basis, is difficult to differentiate from eolian sediment from the same continental source region because both are similar in composition and grain size, an observation first made well over half a century ago by Leuchs (as referenced by Radczewski [1939]). Since hemipelagic fluxes are, depending on proximity of the source, 2 or so orders of magnitude greater than eolian fluxes, a small portion of the original hemipelagic contribution will mask any eolian signal in the sediment. Our task is to understand how far offshore the influence of hemipelagic processes extends. One method of differentiation, but one that requires reasonably well dated cores, would be to examine the amounts and temporal patterns of mineral flux to the core site. Eolian grains should accumulate more rapidly when the source regions are drier, and hemipelagic grains should accumulate more rapidly during wetter times characterized by greater runoff. Moreover, the hemipelagic fluxes should be much larger than eolian fluxes.

We can look for elucidation to cores from the eastern equatorial Pacific, where sediment traps have documented the hemipelagic processes. Two well-dated cores with reliable mineral abundance data [Molina Cruz, 1977, 1978] lie west of the coast of South America, V19-29 at 3°35'S, 83°56'W, about 250 km offshore from the mouth of the Gulf of Guayaquil, and Y71-6-12 at 16°26'S, 77°23'W, about 300 km offshore from Peru. The paleoclimatology of the northern Andes is reasonably well understood and is a history of full lakes and relatively moist climates during glacial times and dry lakes or playas in interglacial times like the present [Hooghiemstra, 1984; Van der Hammen, 1985; Hassenrath and Kutzbach, 1985]. From this scenario and the trap data, one would expect that the sediments in core V19-29, only a few hundred kilometers from the mouth of the Guayaquil River, might record hemipelagic sedimentation with fluxes increasing during glacial times to values in excess of 2000 mg (cm² kyr)⁻¹. A similar but probably more subdued signal may occur in core Y71-6-12, now lying offshore from one of the driest parts of the world, the high desert of southern Peru. The flux pattern of atmospherically transported mineral grains to a core downwind from the northern Andes should show the opposite pattern, higher fluxes during interglacials, and be much lower in magnitude, perhaps tens of mg (cm² kyr)⁻¹. The eolian record that is appropriate to this discussion comes from DSDP site 503B in the eastern equatorial Pacific at 4°03'N, 95°38'W, about 1300 km from the closest land to the northeast [Rea, 1982; Rea et al., 1986].

The mineral flux data from these three cores are displayed in Figure 5. Core V19-29 shows a classical hemipelagic flux pattern, values ranging from 1000 to 3000 mg (cm² kyr)⁻¹ and clearly higher during times of enhanced runoff during and just before glacial stages 2 and 4, and lower during interglacial stages 1, 3, and 5. Core Y71-6-12 at 16.5°S shows the identical basic pattern, although with only one third to half of the flux values of the core to the north. This record is particularly important because it demonstrates that even
near presently hyperarid continental regions, hemipelagic processes may dominate seafloor mineral deposition for several hundred kilometers offshore, in this case even on the seaward side of the Peru Trench. Eolian core DSDP 503B has much lower mineral fluxes in general and relatively higher mineral deposition rates during the drier interglacial stage 5, reflecting the expected eolian flux pattern.

Assigning cores to the hemipelagic or eolian realm is a nontrivial task, especially because we do not know how far offshore the influence of hemipelagic processes extends. Because of this uncertainty, restricting studies of the eolian component of pelagic sediments to cores raised from more than 1000 km offshore is the most conservative approach to avoiding hemipelagic complications.

It is incumbent upon investigators of presumably eolian records derived from cores taken within several hundred kilometers of continents to demonstrate somehow, and not just by assertion, that hemipelagic influences are absent from their sites under all conditions of continental climate. One should beware of "eolian" records derived from cores taken on or adjacent to the continental slope or from marginal seas. The two hemipelagic cores described above were originally interpreted as bearing an eolian signal, and that signal was said to show stronger trade winds during glacial stages, a simple one-to-one correlation [Molina Cruz, 1977, 1978; Molina Cruz and Price, 1977]. This interpretation has remained in the literature, partly because it is intuitively satisfying and partly because it is in agreement with the original work of Parkin [Parkin and Shackleton, 1973; Parkin, 1974; Parkin and Padgham, 1975] (also conducted on likely hemipelagic cores, from the African continental margin). It is, however, clearly incorrect since it was based on a misinterpretation of the mode of deposition of V19-29. In fact, there is not a simple correspondence of wind strength and glacial cycles, as is demonstrated by variability in eolian grain size records (Figure 4). Instead, wind intensity varies on a higher frequency than the longer glacial-interglacial cycles [Janecek and Rea, 1984; Pisias and Rea, 1988; Clemens and Prell, 1990].

The final piece of information that I want to emphasize here is the total amount of mineral material that arrives in the ocean by atmospheric pathways. Terrigenous materials are being supplied to the world's oceans by rivers at a flux rate of about 1.5-2.0 \times 10^{16} \text{g yr}^{-1} [Holland, 1981; Milliman, 1994]. Estimates of dust flux are roughly 5% of the fluvial sediment delivery value. Prospero [1981b] estimated that 0.53-0.85 \times 10^{15} \text{g yr}^{-1} of dust enters the oceans. The more recent estimate of Duce et al. [1991], based on 2 decades of atmospheric sampling, is a bit larger than the earlier estimate of Prospero, 0.91 \times 10^{15} \text{g yr}^{-1}, but at the stated accuracy it seems unlikely that these two estimates are really different. If these flux values are divided by the total area of the oceans and transposed into the unit of mass flux used by oceanographers, they give average eolian mass accumulation rates in the range of 200-250 mg (cm$^2$ kyr)$^{-1}$. In a following section I will compare these values with the generally much lower Quaternary flux values measured in sediment cores from around the world.

A Modicum of Methodology

A brief section describing various laboratory procedures is necessary so that the reader may more fully understand what the data really represent. Most laboratories that work with the mineral component of deep-sea sediments use a version of an extraction procedure that was originally devised to separate materials for X ray mineralogical analyses. Those procedures remove calcium carbonate from the sample, usually with acetic acid, remove opal using either a NaOH (stronger) or a Na$_2$CO$_3$ (milder) leach, remove oxides and hydroxides using a strong reducing agent,
and decant the dissolved materials. There are occasional pitfalls in these procedures, such as the stronger NaOH agent apparently removing some portion of the submicrometer-sized clays present in the samples, but generally these techniques have been widely used for a long time and produce reliable and repeatable results. The accuracy is commonly about ±5%; it is somewhat poorer when working with very small samples. The basic methodology is given by Rea and Janecek [1981a]. Clemens and Prell [1990] and Hovan [1994] offer some slight modifications to the procedures.

The mineral assemblage isolated by the extraction process is the basic information of these studies. If we are convinced, usually by the location of the samples site far from shore and, if important, above the level of any abyssal reworking, that the grains are eolian, then we weigh the extract to determine the concentration (weight percent) of the mineral grains. The samples themselves are then available for geochemical, mineralogical, isotopic, and size analyses.

Grain size analyses are conducted with electronic particle size analyzers that are both fast and accurate, giving repeatable results to better than a 0.1 μm (hundredths of a φ unit; see below). Different kinds of size analyzers have different strengths and weaknesses. The smallest particle that can be measured reliably is 1 μm on a Coulter counter, but is 2 μm or coarser on other analyzers. This difference is important because up to half of all the eolian material in the ocean may be finer than 2 μm in diameter. To my knowledge, no one has reported reliable information on the size distributions of submicrometer particles in deep sea sediments. Results of the size analyses are often reported as φ units. These units are a useful logarithmic size scale such that φ units are the negative logarithm to the base 2 of the grain diameter in millimeters; φ = \(-\log_2 D_{\text{mm}}\). Thus the grain size correspondence is approximately as follows: 10φ = 1 μm, 9φ = 2 μm, 8φ = 4 μm, 7φ = 8 μm, etc. The value most often reported is the median grain size or \(\phi_{50}\), the particle diameter halfway through the total size distribution by mass (fiftieth percentile), and the accuracy is commonly ±0.03φ.

The weight percent of any minor sedimentary component is determined largely by the abundance of the dominant component, often calcium carbonate and sometimes siliceous ooze. Abundance patterns of minor components are always opposite that of the major component. This forced anticorrelation has resulted in erroneous interpretations. To determine the true input history of any one sedimentary component, it is necessary to calculate its mass accumulation rate. The mass accumulation rate, or flux, of sediment to the seafloor is measured in mass per unit area and time, commonly g (cm² kyr⁻¹). That value is calculated by multiplying together the linear sedimentation rate (LSR), measured in centimeters per kiloyear, and the dry bulk density (DBD) of the sediment, measured in grams per cubic centimeters thus MAR \([g (cm^2 kyr)^{-1}] = LSR [cm kyr^{-1}] \times DBD [g cm^{-3}]. The sediment MAR is a much more useful value than just the linear sedimentation rate because it accounts for changing porosities and compaction in the DBD term and therefore quantifies the true amount of material being deposited, a prerequisite for any geochemical budget or cycle studies. MAR values also allow valid comparisons on a global basis. Furthermore, the flux of any individual sediment component can be determined by multiplying the total MAR value by the weight percent of the component of interest. Rea et al. [1991a] give a good example of the usefulness of this technique in deciphering the various sedimentary inputs to a core from the central equatorial Pacific. Eolian MAR values span 3 orders of magnitude, from over 1000 mg (cm² kyr⁻¹) in regions immediately downwind of major source areas, to 1–2 mg (cm² kyr⁻¹) in much of the remote southern hemisphere.

The mineral component that is isolated by the extraction procedure is usually about 60–80% clay minerals, 15–20% quartz, 5–10% feldspars, and occasional other grains. The compositions of the mineral aerosol and of the surficial sediments have been studied extensively [Ferguson et al., 1970; Leinen and Heath, 1981; Blank et al., 1985; Leinen et al., 1986; Leinen, 1989a, b]. Size relationships are such that each mineral component has a characteristic grain size; the clay minerals, the bulk of the eolian load, are much finer grained than the quartz and small amount of feldspar that travel the same distances [Janecek and Rea, 1983; Lever and McCave, 1983]. Volcanic ash present in the sediment also survives the extraction procedures. For eolian paleoclimate studies this material can be viewed as a contaminant. In small amounts it does not bias the flux calculations much, but, since ash particles are usually larger than the associated eolian mineral grains, the grain size data are more apt to be distorted by the presence of minor to modest amounts of ash in the samples. This has been a particular problem for studies of cores raised from the northwest Pacific, downwind from the Japanese and Kuril-Kamchatka volcanoes, where some of the individual sediment samples taken from cores may contain several tens of percent of ash [Rea and Leinen, 1988; Olivarez et al., 1991; Hovan et al., 1991]. For other kinds of investigations, ash layers may provide useful means of correlation and good chronologies. Particle size studies of thicker individual ash layers have been used to interpret the eruption dynamics of large explosive volcanoes [Ledbetter and Sparks, 1979].

THE MODERN SEDIMENTARY RECORD OF EOLIAN DEPOSITION

Enough flux data exist to begin to construct maps of the "present" mass accumulation rates of eolian ma-
Figure 6. Map showing location of Pacific Ocean cores mentioned in the text. Core locations designated by three-digit numbers are sites drilled by the Deep Sea Drilling Project and the Ocean Drilling Program. Those designated with letters and numbers are locations of piston cores.

Figure 7. Mass accumulation rate of dust in the surface sediment of the Pacific Basin. The values usually represent the uppermost Quaternary sample available and occasionally are an average of Holocene rates. Eastern Asia is the largest source of dust to the Pacific. Data sources are given in text.

terials. The eolian MAR data presented here are derived from the uppermost sample in each core rather than being all true Holocene values and as such should be considered as latest Quaternary in age. Further, the natural mix of investigators, locations, and coring techniques imparts some variability to the data set. Nevertheless, these data are the best available for the task and provide a reliable basis both for first-order interpretations of eolian processes and for comparison with the results of 2 decades of sampling by those who study the particulate aerosol.

The maps clearly reveal the first-order aspects of dust deposition at sea. There are only three regions on the continents that supply more than 1000 mg (cm\(^2\) kyr\(^{-1}\)) to the adjacent seafloor. In order of importance they are the deserts of central and western China and Mongolia, the Sahara and Sahel, and Arabia and the Horn of Africa. Moderate amounts of dust extend southeast from southeastern Australia in the westerlies. The great desert of central Australia and the deserts of southern Africa are essentially deflated and provide very little material to the ocean. The size of any potential dust source associated with the loess of southern Argentina is unknown.

Pacific Ocean

Most work on the eolian record in the deep sea has been in the Pacific, so that ocean has by far the best coverage of latest Quaternary dust flux data (Figure 6). Data presented in Figure 7 are largely from information compiled by Rea et al. [1994] with additions in the eastern Pacific from Hovan [1994], in the western equatorial Pacific from Krissek and Janecek [1993], in the western subtropical south Pacific from Schramm and Leinen [1987] and Zhou and Kyte [1992], and from the Lord Howe Rise southeast of Australia by Stein and Robert [1985].

The single overwhelming source of dust to the Pacific is the semiarid and arid region of east central Asia (Figure 7). Dust from this region accumulates at rates greater than 1000 mg (cm\(^2\) kyr\(^{-1}\)) directly downwind from China. Flux values decline to the east toward North America and to the south toward the Intertropical Convergence Zone. Most of the North Pacific is characterized by this Asian source dust; maps of sea surface mineralogy [Leinen et al., 1986] also suggest a small quartz plume extending southwest from the Sonora-Arizona desert. In the eastern and central Pacific the ITCZ with its high rainfall is an effective barrier to further southward transport of Asian dust and dust fluxes fall by about an order of magnitude from north to south across it. The ITCZ in the western Pacific is more variable and a less effective barrier to the transport of Asian dust to the southern hemisphere [Merrill, 1989b]. Detailed studies of the equatorial region indicate a narrow belt of enhanced deposition of dust and other particulates directly beneath the ITCZ in the region of high rainfall [Raemdonck et al., 1986; Hovan, 1994].

The South Pacific is characterized by pelagic clays that accumulate very slowly and broad regions that accumulate eolian dust at rates of only 1–2 mg (cm\(^2\) kyr\(^{-1}\)) (Figure 7). Very little dust moves west in the trade winds from South America; western Pacific val-
Eolian fluxes in the central Atlantic (Figure 8) are at a maximum of over 1000 mg (cm$^2$ kyr)$^{-1}$ in regions close to and directly downwind from the Sahara-Sahel region of Africa. Fluxes fall off to the south toward the equator and decline across the ITCZ by a factor of 5–10 to very moderate values at about 10$^\circ$S.

Indian Ocean

Arabian dust entering the northwestern Indian Ocean has been quantified by Sirocko and Lange [1991], Sirocko et al. [1991], and Clemens and Prell [1990, 1991b]. Hovan and Rea [1991, 1992a] provide information on eolian fluxes to the southern subtropical Indian Ocean.

Dust fluxes to the northwestern Indian Ocean occur in response to strong monsoon winds [Clemens and Prell, 1990; Krissek and Clemens, 1991; Sirocko et al., 1991] and exceed 1000 mg (cm$^2$ kyr)$^{-1}$ in a band paralleling the coast of Arabia and northeastern Africa. Eolian MAR values decrease to the southeast (Figure 9). Fluxes in the southern Indian Ocean are very low, generally less than 1 mg (cm$^2$ kyr)$^{-1}$ beneath the westerlies and only a few mg (cm$^2$ kyr)$^{-1}$ beneath the trade winds. The pattern of very low eolian fluxes in the southern hemisphere seen in the Pacific occurs in the Indian Ocean as well.

The Quest for Provenance

The provenance of dust in cores immediately downwind from the important sources is obvious, but there are both regions and times in the downcore records where the source of the mineral component of the sediments is uncertain. We need to know which continent the dust comes from in order to make proper paleoclimatic interpretations of the eolian source region, to locate past positions of the trade wind–west-
erly boundary or of the ITCZ, and to understand where the eolian grains from one continent becomes masked, say, by the hemipelagic sediments of another. To achieve these distinctions of source, investigators must be able to characterize uniquely the mineral component of deep-sea sediments in any manner possible. Mineralogical data, especially on the <2-µm fraction of those sediments, has been generated for decades, so semiquantitative information on clay and quartz relative abundance is available in the literature [cf. Goldberg and Griffin, 1970; Kolla et al., 1976, 1979, 1981; Kolla and Biscaye, 1977; Leinen and Heath, 1981; Lever and McCave, 1983; Leinen et al., 1986]. All continents supply quartz and illite and a mixture of the other common minerals to the oceans; however, modern investigations are asking more sophisticated questions of the minerals in the sediments.

The field is moving toward geochemical and isotopic characterizations of sediments as well as more discriminatory statistical techniques such as multivariate analysis of mineralogical [Leinen, 1989b; Krissak and Clemens, 1991; Krissak and Janecek, 1993] or geochemical [Leinen, 1987; Olivarez et al., 1991; Kyte et al., 1993a, b] data to determine the nature and abundance of "end-members."

In the late 1960s, Dasch [1969] and Biscaye and Dasch [1971] began to do Rb-Sr and 87Sr/86Sr analyses of deep-sea sediments. Biscaye et al. [1974] applied their techniques to questions of dust provenance in the central Atlantic. At the same time, M. L. Jackson and R. N. Clayton and their coworkers were studying the 818O values of quartz grains isolated from marine and continental sediments in an effort to define the source of the quartz [Clayton et al., 1972; Mokma et al., 1972; Jackson et al., 1973]. A particularly effective early use of this technique was to demonstrate that the quartz in the soils of the Hawaiian islands all came from fallout of Asian dust [Rex et al., 1969]. Dymond et al. [1974] showed the same thing on the basis of K-Ar, Rb-Sr and 87Sr/86Sr information derived from the micas in the same soils.

Until recently the small amount of minerals that could be extracted from a sediment sample precluded more sophisticated geochemical and isotopic analyses of eolian dusts from most deep-sea sediments. Analytical tools are becoming more sensitive, and in the past several years various investigators have begun to analyze the geochemistry and especially Rb-Sr and Sm-Nd isotope systematics of marine sediments. S. J. Goldstein and coworkers have characterized the Rb-Sr and Sm-Nd relationships in both the material leaving the continents and that found in deep-sea sediments [Goldstein and O'Nions, 1981; Goldstein et al., 1984; Goldstein and Jacobsen, 1987, 1988]. F. E. Grousset and his coworkers have examined Nd and Sr isotopic signatures of aerosols and sediments to trace transport pathways [Grousset and Chesselet, 1986; Grousset et al., 1988, 1992a, b; Grousset and Biscaye, 1989; Leinen et al., 1987, 1989a], Olivarez and Owen [1989], Olivarez et al. [1991], and Kyte et al. [1993a] have determined the geochemistry of both the mineral extract and bulk surface sediment with the intent of differentiating among continental, volcanic, biogenic, hydrothermal, and other end-members. A recent success in using isotopes of Sr and Nd to determine provenance of dust was achieved by Grousset et al. [1992b], who were able to demonstrate clearly that the dust particles in an Antarctic ice core were derived from the Patagonian loess of southern Argentina and are not from any of a number of other sources that had been speculated upon.

We are in the process of characterizing the rare earth geochemistry and Sr and Nd isotope characteristics of surficial samples form the Pacific Ocean. The first results of this work show three distinct sources for the extracted mineral component of surficial sediments; eastern Asia, particularly the China loess deposits, the volcanics of the Kuril-Kamchatka arc, and the andesites of western America (Figure 10) [Nakai et al., 1993]. We hope that analyses of our full suite of sediment samples will allow us to determine the aerial extent of the region of dominance of each of these components and eventually allow us to differentiate among them downcore.
Figure 11. Map showing estimates of the rate of deposition of mineral aerosol in the world ocean, based on considerations of atmospheric transport [after Duce et al., 1991]. Note the general similarity between this map and the maps derived from analyses of deep-sea sediments.

Discussion

As I noted above, the most recent results of studies of aerosols indicate that the average MAR of dust over the entire ocean is in the range of 200–250 mg (cm² kyr)⁻¹. In map view, the global fluxes of mineral aerosol to the ocean as determined by atmospheric scientists (Figure 11) [Duce et al., 1991] resemble the patterns indicated in Figures 7, 8, and 9 reasonably well. Important mineral input to the seafloor occurs downwind from eastern Asia, Saharan Africa, Arabia and southeastern Australia. Low flux values characterize the southern hemisphere oceans.

It is clear from both the sediment-derived flux values (Figures 7, 8, and 9) and from the map provided by the atmospheric scientists (Figure 11) that dust flux exceeds 250 mg (cm² kyr)⁻¹ in only a rather restricted portion of the ocean, mostly downwind from the major source regions. Broad regions of the South Pacific and Indian Ocean, and probably most of the southern ocean are characterized by remarkably low dust flux values, rarely exceeding a few mg (cm² kyr)⁻¹. For the pelagic ocean, therefore, the average flux value of 200 to 250 mg (cm² kyr)⁻¹ is too high, perhaps by as much as a factor of 5. Unless there is significant dust deposition near shore, where it mixes with other sediments and therefore can no longer be quantified, overall values of dust flux estimates to the pelagic ocean must be reduced significantly to be brought in line with the data presented here.

EOLIAN RECORDS OF QUATERNARY CLIMATES

Milankovitch Cycles

One of the most important advances in understanding climate change has been the recognition that the variability of the Earth's orbit serves to change the areal and seasonal distribution of incoming solar energy and thus alters climate. This mechanism of climate change was first envisioned in its near-modern form in the late nineteenth century by Croll [1864, 1875] and quantified by Milankovitch in the years between World War I and World War II [Milankovitch, 1930, 1941]. Hays et al. [1976] first documented Milankovitch (Earth orbital) cycles in pelagic records of global climate. Since 1976, the presence of variability at the 100-kyr periodicity associated with eccentricity (the degree of circularity of the orbit), the 41-kyr periodicity associated with obliquity (tilt of the rotational axis with respect to the plane of the ecliptic) and the 23- and 19-kyr periodicities associated with precession (of the equinox) have been found in a great many records of oceanic and atmospheric climate change [e.g., Imbrie et al., 1992]. This orbital forcing is the major cause of climate change on time scales of thousands to hundreds of thousands of years.

To quantify the degree of orbital forcing in any paleoclimatic proxy record of sufficient length requires spectral analysis of data that already have a tightly constrained chronology. The chronologic-stratigraphic standard used for this propose is the δ¹⁸O record of marine calcite, known to be an excellent proxy for changes in global ice volume during the middle and late Quaternary [Imbrie et al., 1984]. Thus most high-resolution studies of Quaternary climate change begin with the establishment of a high-quality oxygen isotope record. Proxy data, well constrained temporally, are then subjected to spectral analysis to determine the relative amount and periodicity of cyclic variation in the record and to determine the coherence (analogous to correlation coefficient) and phase (lead-lag relationships) between one proxy record and another at each orbital period. In addition to the primary variability at about 100, 41, 23, and 19 kyr, there are important concentrations of variance at periods of approximately 30–35 kyr and 52 kyr in the eolian record of continental climate and past atmospheric circulation. Such "nonprimary" periods occur as heterodynes of the primary orbital periods and denote nonlinear responses of the climate system to orbital forcing. Table 1 provides a listing of the periods of orbitally induced variation in eolian processes determined for the cores described below. Recently, Imbrie et al. [1992] have summarized the techniques of spectral analysis as applied to paleoclimatic records.

North Pacific

There has been more than a decade of downcore studies of eolian processes based on cores from beneath the North Pacific westerlies. These studies have
TABLE 1. Orbital Variability in Middle and Late Quaternary Proxy Indicators of Eolian Processes and Paleoclimates

<table>
<thead>
<tr>
<th>Core</th>
<th>Proxy</th>
<th>Periods of Variability, kyr</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Pacific</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC14-105</td>
<td>% quartz</td>
<td>23, 100</td>
<td>1</td>
</tr>
<tr>
<td>KK75-02</td>
<td>dust $\phi_{50}$</td>
<td>23, 41, 104</td>
<td>2</td>
</tr>
<tr>
<td>V20-120</td>
<td>% quartz</td>
<td>50, 100</td>
<td>3</td>
</tr>
<tr>
<td>V21-146</td>
<td>dust MAR</td>
<td>19, 41, 100</td>
<td>4</td>
</tr>
<tr>
<td>V21-146</td>
<td>dust $\phi_{50}$</td>
<td>33, 50, 100</td>
<td>4</td>
</tr>
<tr>
<td>Equatorial Pacific</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC11-210</td>
<td>dust $\phi_{50}$</td>
<td>20, 35, 123</td>
<td>5</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC27-61</td>
<td>dust MAR</td>
<td>19–23, 100</td>
<td>6</td>
</tr>
<tr>
<td>RC27-61</td>
<td>dust $\phi_{50}$</td>
<td>23, 29–35, 54</td>
<td>6</td>
</tr>
<tr>
<td>ODP 722</td>
<td>dust $\phi_{50}$</td>
<td>18–23, 33, 59, 100</td>
<td>7</td>
</tr>
<tr>
<td>ODP 722</td>
<td>% lithic</td>
<td>19, 41, 100</td>
<td>7</td>
</tr>
<tr>
<td>ODP 722</td>
<td>mineralogy</td>
<td>23, 35, 41, 100</td>
<td>8</td>
</tr>
<tr>
<td>Atlantic Ocean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODP 663</td>
<td>% lithic</td>
<td>19–23, 41, 100</td>
<td>9</td>
</tr>
<tr>
<td>ODP 663</td>
<td>phytoliths</td>
<td>19–23, 41, 100</td>
<td>9</td>
</tr>
<tr>
<td>ODP 663</td>
<td>Melosira</td>
<td>19–23, 41, 100</td>
<td>9</td>
</tr>
</tbody>
</table>

References are as follows: 1, Pisias and Leinen [1984]; 2, Janecek and Rea [1984]; 3, Morley et al. [1987]; 4, Hovan et al. [1991]; 5, Rea et al. [1991a]; 6, Clemens and Prell [1990, 1991a]; 7, Clemens and Prell [1991b]; 8, Krissek and Clemens [1991]; 9, deMenocal et al. [1993].

*For 0- to 500-kyr portion of the record.

concentrated on determining the nature of the Quaternary flux record of eolian material in the North Pacific, the grain size record of past atmospheric circulation, and the influence of orbital variability on these processes. Pisias and Leinen [1984] examined the quartz abundance record in core RC14-105, thought to be a proxy for dust input to the ocean. A spectral analysis of that quartz record demonstrated the presence of variability at the 100-kyr period of orbital eccentricity and the 23-kyr period that corresponds to precession. They found the variability in the quartz record to be coherent and in phase with the $\delta^{18}O$ record of maximum ice volume, indicating that eolian deposition varied with climate, with more quartz entering the ocean during glacial times.

Janecek and Rea [1984, 1985] presented the results of examining the eolian sediment at core KK75-02 from beneath the zonal westerlies (Figure 6). That core provided the first long grain size record of paleowind intensity. Data from this core (Figure 12) show dust accumulation rates of 100–400 mg (cm$^2$ kyrm$^{-1}$), with two broad lows centered approximately at interglacial stages 5 and 13/15. Eolian grain size shows smaller amplitude and shorter-wavelength peaks in the upper portion of the core and larger amplitude and longer-wavelength fluctuations in the older portion of the core, in sediments older than about 250 kyr.

Spectral analysis of the eolian grain size found distinct concentrations of variance centered at 104, 41, and 23 kyr, the periods corresponding to eccentricity, tilt, and precession. Unlike most records of climate variability where the 100-kyr power forms the dominant peak, more of the variance in the KK75-02 grain size record is concentrated at 41 kyr than at either of the other periods. All major spectral peaks are coherent with orbital forcing. Phases are such that coarser

![Figure 12](image-url)
grains (stronger winds) occur with both minimal tilt and maximal precession, both of which are conditions for ice growth and glaciation. For eccentricity, however, phase analysis shows that larger grains are in phase with maximum eccentricity, a condition that characterizes interglacial times [Janecek and Rea, 1984]. This result is both counterintuitive and opposite to the phase relationships between grain size and orbital variability for the shorter periods.

Morley et al. [1987] examined the quartz abundance record in northwest Pacific core V20-120. They found that the dominant period of variation of that record was about 50 kyr, with lesser amounts of variance concentrated at 100 kyr. The significance of the 50-kyr spectral peak, perhaps a harmonic of eccentricity, in this core is not clear; it is possible that the quartz record at this latitude is complicated by ice rafting during glacial times [Morley et al., 1987].

Pye and Zhou [1989] provide a history of Holocene and late Pleistocene dust transport based on records from mainland China. They note reduced dust transport in the Holocene from enhanced late Pleistocene values. Rea and Leinen [1988] showed in a study of northwestern Pacific cores that for the last 30 kyr the latitudinal position of the dust flux maxima remained fixed in position at 35°–42°N, directly downwind from the Asian source region. Factor analysis of the clay mineral assemblage of those sediments suggests three distinct source regions for the mineral component: andesitic soils (likely from Japan), loess, and weathering products from northeastern Asia [Leinen, 1989b].

The best record of Quaternary eolian deposition in the North Pacific is derived from core V21-146, a carbonate-bearing core raised from Shatsky Rise. The core site (Figure 6) is beneath the prevailing westerlies directly downwind from the Chinese-Mongolian source regions and at the latitude of maximum dust fluxes during both glacial and interglacial times [Rea and Leinen, 1988]. V21-146 is the only core from the North Pacific to have a good δ18O record and thus a well-constrained chronology. Hovan et al. [1989, 1991] used samples from this core to construct a detailed record of eolian fluxes and grain size that spans the last 530 kyr (Figure 13). They were able to show a clear relationship between dust flux maxima and glacial stages and suggested a direct link of times of enhanced dust deposition to times of loess formation in China. In fact, the good timescale provided to the dust flux data by the δ18O record allowed a modest revision of the loess chronology [Hovan et al., 1989]. In addition to the obvious glacial-aged dust flux maxima, there is a general increase in the rate of dust deposition over the last 530 kyr indicative of a continued long-term drying of central and eastern Asia [Pye and Zhou, 1989], probably a reflection of continuing uplift of the Himalayas.

Spectral analysis of the dust flux record from V21-146 [Hovan et al., 1991] demonstrated the presence of variability at periods of 100, 41, and 19 kyr that is both coherent and in phase with the δ18O record of global change. These data suggest that the process of loess formation in Asia is closely linked to changes in northern hemisphere ice volume. Eolian grain size varies at higher frequency than does the flux or δ18O record; sediments older than about 250 or 300 kyr may display more longer-period size variability than younger material (Figure 12). The eolian grain size record shows variability at periods of 100, 50, and 33 kyr, but the grain size record is coherent with the V21-146 δ18O
record only at 100 and 33 kyr. Phase analysis shows the 100-kyr spectral peak in grain size to be 180° from conditions of maximum glaciation, the same result as found by Janecek and Rea [1984, 1985] for core KK75-02. We have not fully explained why coarser eolian grains should be associated with interglacial conditions at the 100-kyr forcing but with glacial conditions at shorter periods. One possibility is latitudinal shifts of the zone of maximum wind intensity to the south during glaciations [Hovan et al., 1991].

The flux record from V21-146 represents the Quaternary history of the Asian dust source to the Pacific (Figure 13). As this source now dominates all but the easternmost Pacific Ocean, we expect to find this pattern of glacial-aged flux maxima in all cores that lie north of the ITCZ and more than, very roughly, 1500 km west of North and Central America. V21-146 also provides the first good example of how the terrigenous component of a pelagic core can be used to link continental and marine records of global change, in this case the China loess deposits and the marine δ18O record. There is no other way to achieve this important goal of paleoclimatologists.

Equatorial Pacific

Earlier work on the eolian record of the equatorial Pacific was conducted on samples from DSDP hole 503B (Figure 6) [Rea, 1982; Rea et al., 1986]. The dust flux record in the eastern equatorial Pacific south of the ITCZ is such that flux maxima are of interglacial age back to stage 9, and minima occur during glacial (Figure 14).

This pattern of enhanced interglacial dust fluxes corresponds to the that of climatic variability in the northern Andes which is one of full lakes during glacial times and low to dry lakes and playas during interglacial times [Hooghiemstra, 1984; Van der Hammen, 1985]. Documentation of this flux pattern characterized by interglacial-aged flux maxima for the equatorial Pacific south of the ITCZ allows us to use recognition of this South American pattern to determine if and when any particular core lay north or south of the ITCZ. Inasmuch as the latitudinal position of the ITCZ records the relative circulatory energy of the hemispheres, shifts in its position are an indication of hemispherical climate change [Rea, 1990; Rea et al., 1994].

Core RC11-210, raised from just north of the equator at about 140°W, is the best studied core from the equatorial Pacific. It has a 945-kyr record of oceanographic and climatic change that provides a long history of atmospheric and oceanic variability. The sediments from RC11-210 contain a variety of paleoclimatologic and paleoceanographic proxy records, including a "classic" equatorial Pacific carbonate record with abundance maxima occurring during glacial times, an adequate (from planktonic δ18O) record, records of opal and carbon deposition, statistical data on faunal assemblages, and a record of atmospheric dust transport of dust spanning nearly one million years [Chuey et al., 1987; Pisias and Rea, 1988; Rea et al., 1991a]. Dust MAR data (Figure 14) show flux maxima during interglacial stages 5 and 7 and during glacial stages 10 and 12 (the uppermost flux values are not reliable, as those samples were mistreated (dropped on the floor) in the laboratory). Further downcore the pattern changes back to the upper pattern, and dust flux maxima occur in conjunction with interglacial stages 15, 19, and 21. Some of the amplitude of the flux peak at 100 kyr is from an ash layer, and so this peak is
not truly representative of the input of continentally derived mineral grains to this site.

The eolian grain size record (Figure 14) from RC11-210 is similar to that derived from KK75-02 in that the amplitude and wavelength of the size variability changes at about 250–300 ka from lower amplitude and shorter wavelength in the upper portion of the core to higher amplitude and longer wavelength in older sediments. The time of this change in variability is denoted by a period characterized by small grain size and minimal variability that occurs at the same time as the change from one flux pattern to another. In sediments older than about 875 kyr the variability in eolian size is reduced markedly; in the record of climatic processes the amplitude of variability in wind intensity increases 25 kyr before (leads) the variability increase in calcite flux and in amplitude of the \(^{18}\)O signal [Chuey et al., 1987]. The change in the nature of variability of paleoclimatic proxy indicators at about 300 ka has been termed the mid-Brunhes climate event (MBCE) [Janssen et al., 1986; Rea, 1990].

Pisias and Rea [1988] conducted a spectral analysis of the eolian size and radiolarian assemblage data, a proxy for equatorial upwelling, for core RC11-210. Since the MBCE causes a statistical discontinuity in the eolian time series, the spectral analysis was conducted in sediments ranging in age from 402 to 774 kyr. Analysis of the \(^{18}\)O record from this portion of the core shows the 100- and 23-kyr power anticipated, all coherent and in phase with the Spectral Mapping and Prediction (SPECMAP) standard record [Imbrie et al., 1984]. The eolian and upwelling proxies, however, each have a predominant periodicity of about 31 kyr. This 31-kyr spectral peak is coherent and in phase between the radiolarian record of upwelling and the dust grain size record of wind intensity, demonstrating for the first time a quantitative link between atmospheric and oceanic circulation in the paleorecord [Pisias and Rea, 1988]. Further work showed that this same spectral peak, likely a combination of orbital eccentricity and tilt, dominates the eolian size and upwelling assemblage data throughout the entire length of RC11-210 and that powers associated with the periods of eccentricity and precession also are present in the size record [Rea et al., 1991a].

Indian Ocean

Clemens and Prell [1990, 1991b] have quantified the MAR and grain size of eolian materials delivered from the arid regions of Arabia to the northwestern Arabian Sea in piston core RC27-61 (Figure 15) and at ODP site 722 (Figure 15), both from the elevated crest of Owen Ridge. The Quaternary record of that process (Figure 15) shows regular variability in dust flux, with 3 to 5 times as much dust entering the ocean during glacial times as during interglacials. The eolian grain size record of paleowind intensity shows modest variability in sediments younger than about 500 kyr and higher-amplitude variability in older sediment (Figure 15). This change is in the same sense as that observed in the Pacific but occurs at a somewhat older age.

Spectral analysis of the eolian flux data from piston core RC27-61 shows the presence of the primary orbital periodicities of 100, 41, 23, and 19 kyr that are coherent and in phase with maxima in global ice volume [Clemens and Prell, 1990]. Note the change in the character of the grain size variability at 400–500 kyr ago. (bottom) Eolian flux and \(^{18}\)O values from equatorial Atlantic ODP core 663; data from deMenocal et al. [1993]. Odd-numbered interglacial stages are indicated.
precession periodicities but little at 100 kyr [Clemens and Prell, 1991a, b; Clemens et al., 1991]. Wind intensity data and upwelling proxies from the Arabian Sea vary coherently and are generally in phase for both precession and obliquity, documenting wind-driven control of oceanic upwelling from the Indian Ocean paleorecord [Clemens et al., 1991]. Clemens and his coworkers conclude from their spectral analyses that the wind systems of the Arabian Sea are responding primarily to intraregional monsoonal cycles dominated by shorter-period, dominantly precessional, variability and that the continental aridity cycles are responding to extraregional, perhaps global, climatic forcing. In contrast to the southern hemisphere trade wind record at RC11-210, there is no indication of an increase in the amplitude of variability in the site 722 eolian grain size record at about 875 ka, implying that this event which strongly influenced the nature of the trade winds had minimal effect on the Arabian monsoon.

Furthermore, the eolian grain size signal from the Arabian sea contains some spectral power at 52 and 29 kyr that is in phase and coherent with similar variability expressed in core RC11-210 from the equatorial Pacific. This has led Clemens and Prell [1991a] to examine the effects of orbitally modulated insolation at various latitudes and months. They found that conditions for May at the latitude of 30°S exhibit the highest coherency to these combination periodicities. As in the modern monsoon, the heat energy of the southern subtropical gyre is important to the paleointensity of the southeast trade winds and the Arabian monsoon [Clemens and Prell, 1991a]. This is a possible reason for the observed linkage between the equatorial Pacific and Indian Ocean wind intensity records.

In an effort to further quantify the sources of dust to ODP site 722, Krissek and Clemens [1991] analyzed the eolian component of those sediments for their bulk mineralogy. The 500-kyr-long record was subjected to a factor analysis which showed the presence of four mineral assemblages, three indicating arid source regions and one from a more humid source. The mineralogy and the factor loadings showed high-frequency variability indicating changing conditions in the source areas at the Milankovitch periods of 100, 41, and 23 kyr and at a combination periodicity of 33 to 38 kyr [Krissek and Clemens, 1991]. Fagel et al. [1992] examined the clay mineralogy of sediments from ODP site 721, adjacent to site 722 on Owen Ridge, in the age span of 1.2 to 2.7 m.y. They observe the primary orbital periodicities in the clay mineral data as well as secondary periodicities of about 25, 31, and 60 kyr. One objective of the Fagel et al. [1992] study was to document the change in forcing that may have occurred in conjunction with the onset of major northern hemisphere glaciation, now thought to have occurred about 2.6 Ma [Cande and Kent, 1992]; results show the rise in importance of obliquity in relation to that of precession in determining climate change at that time. Similar changes had been noted earlier by Bloemendal and deMenocal [1989] and deMenocal et al. [1991] in the signal provided by magnetic susceptibility (a very good indicator of percent terrigenous material in a pelagic sediment) of sediments in sites 721 and 722. Their data show, in overlapping 400-kyr windows, the relative decline in importance of precession and rise in obliquity in the eolian proxy from 3.2 Ma to present, with the largest change coming about 2.5 Ma.

Atlantic Ocean

There is a nearly 35-year gap between the time Radczewski [1939] reported on the cinnamon-colored quartz in the Meteor cores and the initial downcore work of Parkin [Parkin and Shackleton, 1973; Parkin, 1974] and Sarthein [Sarthein and Diester-Haass, 1977; Sarthein, 1978] on African/Saharan quartz in the same region. Radczewski [1939] noticed decreasing abundance and grain size of the eolian quartz for about 1000 km downwind from the source region in northwestern Africa and noticed that sediments of glacial age also were characterized by eolian quartz from Africa, an important new understanding in 1959. Game [1964] examined an eastern Atlantic dust sample collected by the second mate of a passing freighter and observed clear quartz and freshwater diatoms. The clear quartz led him to suggest that the abundance of only red-brown quartz might not be such a good indicator of the relative amount of eolian material in deep-sea sediments [Game, 1964]. Sarthein et al. [1981] conducted a study similar to that of Parkin and Shackleton [1973] and Parkin [1974] and examined the larger than 6 μm fraction of the mineral component of deep-sea sediments off North Africa. Parkin interpreted coarser grains during glacial cycles as an indication of stronger trade winds during those times. Sarthein et al. [1981] found smaller grains for the time of mid-Holocene climatic optimum than are found for present-day sediments, indicating less intense winds, and coarser grains indicating stronger winds at the 18-kyr horizon corresponding to the last glacial maximum. Pollen studies associated with dust input information [Sarthein et al., 1982] indicated that the eolian source region was more humid during the early to middle Holocene and drier during the last glacial maximum.

François et al. [1990] determined the flux of the terrigenous component (determined by difference assuming a simple two-component (CaCO3 and minerals) sediment) in deep-sea cores raised from the Ceara Rise and the Sierra Leone Rise. Mineral MAR values from the Ceara Rise in the western equatorial Atlantic relatively far from the African source region are 300–1500 mg (cm2 kyr)−1 and probably reflect hemipelagic sedimentation from the Amazon River. In the eastern equatorial Atlantic the Sierra Leone Rise record, with mineral fluxes of 190–700 mg (cm2 kyr)−1, is much more likely to be representative of eolian deposition.
Those cores show that eolian fluxes increase two- or threefold from the Holocene back to the last glacial maximum [François et al., 1994].

Longer flux records from ocean drilling cores [Ruddiman and Janecek, 1989; deMenocal et al., 1993] and from equatorial Atlantic piston cores [Rea et al., 1994] show considerable downcore variation in dust accumulation and no obvious relationship between glacial or interglacial stage and dust flux (Figure 15). In this regard the equatorial Atlantic record of African aridity is more complex than that of either the Pacific or Indian Ocean.

E. M. Pokras and his coworkers have identified another sedimentary component in pelagic sediments that provides a paleoclimatic record of the tropical African source region, the freshwater diatom Melosira. Abundance and accumulation rate of this diatom record the wetting and drying of lakes in north equatorial Africa, south of the Sahara [Pokras and Mix, 1987; Pokras, 1991]. Spectral analysis of those records indicates a strong precessional signal suggesting low-latitude, possibly monsoonal control of the climate of the source region [Pokras and Mix, 1987].

DeMenocal et al. [1993] examined a 900-kyr-long record of terrigenous material, opal phytoliths (from grasses and wind transported), and Melosira from ODP site 663 (Figure 15) to determine the nature of probable orbital forcing on those sedimentary components. They found strong 100- and 41-kyr forcing in the terrigenous and phytolith accumulation records and precessional power in the Melosira record. The interpretation of these results is that monsoonal processes determine climate change in the region characterized by freshwater bodies containing Melosira and that the terrigenous and phytolith input, from farther north, is somehow influenced by high-latitude climate change. Sea surface temperature records from the mid-latitude North Atlantic are coherent and in phase with the variability of terrigenous deposition at the equator, suggesting this oceanographic parameter as the link. The terrigenous and Melosira records are coherent and in phase with each other at 41 kyr, strongly coherent at 30 kyr, and marginally coherent at 19–23 kyr [deMenocal et al., 1993]; this is the first observation of the 30- to 35-kyr period of variability, common in Pacific and Indian Ocean records, in the eolian record of the Atlantic.

Overview of the Quaternary Eolian Record

The mass accumulation rate of eolian dust to the seafloor provides a record of the climate of the eolian source region. Spectral analysis of the variability of that signal always indicates important amounts of power concentrated at the orbitally related period of the 100-kyr eccentricity cycle, usually has 41-kyr obliquity power, and commonly contains precessional power at the 19- and 23-kyr periods (Table 1). The paleoclimate of the semiarid and arid regions supplying dust to the North Pacific Ocean and Arabian Sea varies in a regular manner between dry glacial times and more humid (more vegetated) interglacials. Spectral analysis of a central Atlantic record gives the same result, although the long-term variability is not as obvious there (Figure 15). The existence of loess layers in both Argentina and New Zealand suggests that dust flux patterns may be similar in oceans downwind from those sources. Northwestern and western South America is the only eolian source region yet documented to have the opposite signal: the Andean region is dryer during interglacials and provides more dust to the Pacific south of the ITCZ during those times.

The eolian grain size record of wind intensity always shows a higher-order variability than glacial-interglacial cycles, so the generalization that glacial stages are characterized by stronger winds is not valid. The 100-kyr spectral peak is present in the eolian grain size signal but usually is secondary in importance to the shorter periods. Variability at the 41-kyr period of obliquity is curiously absent from most eolian grain size records. Precession dominates this signal in monsoonal regions such as the Arabian Sea. In the Pacific there is considerable variability concentrated in the range of 30–35 kyr. This 30- to 35-kyr power appears in one form or another in records of eolian transport in every ocean. There are three combination frequencies that may contribute to this forcing which can be represented as (1) 1/100 kyr + 1/41 kyr = 1/29 kyr, (2) 1/23 kyr − 1/100 kyr = 1/30 kyr, and (3) 1/19 kyr − 1/41 kyr = 1/35 kyr. Clemens and Prell [1991a] associated combination tone 3 with insolation at 30°S in May, an indication of the influence of the southern hemisphere subtropical high in the wind intensity data in the Arabian Sea. Pisias and Rea [1988] showed that the wind intensity and upwelling signal beneath the southern hemisphere trade winds in the equatorial Pacific is dominated by and coherent with tone 1. Hovan et al. [1991] found 33-kyr power in the grain size record of the northern hemisphere westerlies. These combination tones centered at 32 or 33 kyr are important causes of variation in atmospheric circulation, and thus sea surface circulation, and their nature needs to be more fully investigated. Evidence of orbitally related forcing of wind intensity at a period of 50–55 kyr also occurs, but is of lesser magnitude than the 30- to 35-kyr power. This longer period may be a combination of precession and obliquity (1/23 kyr − 1/41 kyr = 1/52 kyr).

Pisias and Rea [1988] and Clemens et al. [1991] have demonstrated that the eolian grain size signal of wind intensity is coherent and in phase with proxy records of equatorial and monsoonal upwelling. These two studies provide the first direct evidence of wind-driven sea surface circulation in the paleoclimatic and paleoceanographic record. Proxies of paleoproducitivity vary in a similar manner to records of wind intensity and not in a manner that can be quantitatively
linked to dust flux. In the equatorial Pacific, dust flux maxima occur during interglacial times (back to stage 7; Figure 14) and the flux maxima of organic carbon, calcite, and opal all occur during glacial stages [Rea et al., 1991a]. Therefore the suggestion that dust input supplies important quantities of limiting nutrients, such as Fe, to the sea surface and in that manner controls productivity [Martin and Fitzwater, 1988] is found wanting in these equatorial records of paleoceanographic variability.

Several changes in the nature of variability of paleoclimatic proxy indicators occurred about 250,000–300,000 years ago, defining what has been termed the mid-Brunhes climate event [Jansen et al., 1986; Rea, 1990]. Changes in the nature of variability of the eolian grain size records from westerly cores KK75-02 [Jansen and Rea, 1985] and V21-146 [Hovan et al., 1991] and trade winds core RC11-210 [Chuey et al., 1987] indicate that the nature of atmospheric circulation in the Pacific responded to this event. Other changes in variability about this time have been reported by Pisias and Leinen [1984] for opal flux information from the northwestern Pacific and by Sancetta and Silvestri [1984], Schramm [1985], and Pisias and Rea [1988] for siliceous plankton assemblage data.

Jansen et al. [1986] compiled a global catalog of changes in variability of paleoceanographic indicators that occurred from about 250 ka to 500 ka. Changes that occurred nearer to 500 ka include an upcore increase in the amplitude of the carbonate abundance fluctuations in many Pacific deep-sea cores, an increase in the amplitude of the δ¹⁸O signal of global climate/ice volume variability, and an upcore decrease in the size of eolian grains and amplitude of eolian variability in the Arabian Sea [Clemens and Prell, 1991b].

The several changes that happened about 250 or 300 ka are coincident with the transition from oxygen isotope glacial stage 8 to interglacial stage 9. At this same time the pattern of eolian fluxes to equatorial Pacific cores DSDP 503B and RC11-210 changed from an older pattern of high fluxes during glacial to a younger pattern of high fluxes during interglacial times. All of our indications from the modern environment are that dust from eastern Asia dominates the equatorial Pacific south to the ITCZ and dust from northern South America dominates in trade wind regions south of the ITCZ (Figure 10). Since high fluxes during glacial times have been demonstrated as the Asian aridity signal, I interpret this synchronous change in eolian flux pattern along the equator as reflecting a latitudinal shift in the position of the ITCZ, such that the ITCZ lay at least 5° further south prior to stage 9. The accumulation pattern in RC11-210 reverts back to that characteristic of the southern hemisphere about 550–600 ka. Inasmuch as the latitude of the ITCZ is determined by the relative circulation energy in each hemisphere, shifts in its position record independent changes in the circulation intensity of one hemisphere, not matched by changes in the other.

This concept, termed hemispherical asymmetry by Flohn [1981], is clearly important in considerations of long-term climate change (see below). In the case of the equatorial Pacific data, the implication is that during interglacial stage 9 the southern hemisphere became relatively more energetic than the northern, resulting in a northward offset of the ITCZ. Inasmuch as the location of the ITCZ is important to equatorial circulation, upwelling, and productivity in all oceans, this kind of data has important ramifications to much of paleoceanography.

The community of scientists working on the paleoclimatic records provided by ice cores have long noted that the abundance of mineral particles increases by an order of magnitude or more in glacial-aged ice [cf. Thompson and Mosley-Thompson, 1981; Petit et al., 1990]. The Vostok ice core with the longest published record shows an increase in the mineral aerosol, as defined by Al content, during glacial stages 2, 4, and 6 [Petit et al., 1990; Jouzel et al., 1993]. Various paleoclimatic interpretations have been drawn from these observations. In the context of this review, I note that what is really needed is mass accumulation rate of the mineral aerosol to the ice cores for the same reasons that we need these data from deep-sea cores. Further, the ice core dust input values almost certainly record regional aridity in the mid to high latitudes of the appropriate hemisphere and have little or nothing to do either with global climate changes, other than the fact that the responses are similar, or with wind speed. Because of the distances involved and the rainfall barriers at the ITCZ and subpolar low, it is only a remote possibility that any northern hemisphere dust reaches Antarctica. This is emphasized by the geochemical detective work of Grousset et al. [1992b], who documented the Argentine loess deposits as the source of particles in the Dome-C core of Antarctica. A similar study of the ice age particulates in the ice cores from Canada or Greenland would be able to discern whether the closer Alaskan loess, midcontinent U.S. loess, or much more distal China loess were the source of the northern hemisphere particulates.

We do not yet fully understand why climates change. Partial answers such as changing concentration of atmospheric gasses, orbital variability, and oceanic and atmospheric heat transport are all important. The information gathered here suggests strongly that during the last glacial maximum much of the northern hemisphere and probably the mid to high latitudes of the southern hemisphere were characterized by a severalfold, but not an order of magnitude, increase in the amount of dust being transported in the upper troposphere. Although it seems generally accepted by the modeling community that this increase in dust loading would act to cool the planet [Kutzbach, 1987; Peteet et al., 1992], such a process has been
incorporated into general circulation models in only a preliminary manner. Joussaume [1993] has tried to model the assumed dust levels of the last glacial maximum using a soil moisture estimation within an atmospheric general circulation model. She was able to approximate the seasonality of the dust generation process and the direction of change, less dust downwind from South America and more everywhere else, but the magnitudes of the changes in her model were far too small [Joussaume, 1993]. Harvey [1988] presents results based on energy balance model that indicate that doubling the global aerosol may, in conjunction with changes in insolation, account for over 2° of cooling during the last glacial maximum. Since we find that the northern hemisphere is much dustier than the southern, any cooling or feedback effect of enhanced glacial-aged dust loading should be much stronger north of the equator. This problem seems a natural for a continued modeling approach using general circulation models.

LONG-TERM RECORDS OF EOLIAN DEPOSITION

The Atlantic Record of North African Aridity

Mineral grains have been blowing from Africa and North America into the central and North Atlantic ever since the ocean formed [Lever and McCave, 1983]. R. Stein has examined the accumulation of the mineral component in DSDP cores from west of Africa, site 397 at about 27°N on the lower continental slope (Figure 8) [Stein, 1985a] and site 366 from just north of the equator on the Sierra Leone Rise (Figure 8) [Stein, 1985b]. Site 397 displays very high mineral fluxes of 2000–8000 mg (cm² kyr⁻¹) and is, at least occasionally, characterized by fluvial sediments [Stein, 1985a] and therefore may not be a good core for a purely eolian sedimentation history. Site 366 from atop the Sierra Leone Rise may contain a long history of climate change from subequatorial, southern hemisphere, Africa. The record shows that low fluxes of very fine mineral grains characterized the Oligocene through middle Miocene. The latest Miocene, 6 to 5 Ma, is characterized by enhanced mineral flux and coarser grains. The Pliocene-Pleistocene history of equatorial Africa is one of low fluxes and smaller grain size in the lower to the middle Pliocene and an increase in both the flux and grain size of mineral grains in approximately the past 2.5 m.y.

Sarnthein and Fenner [1988] note an increase in African aridity at about 2.4 Ma based on some of the same information examined by Stein and further suggest up to a threefold increase in wind speed at this same time, based on considerations of the size of wind-transported grains. Pokras [1989], in a study of terrestrial siliceous microfossils from equatorial ODP cores 662 and 664, noted that his data are consistent with further drying of that region at about 2.5 to 2.3 Ma. All these changes in the time span of about 2.4 m.y. are associated by the authors with the onset of major late Cenozoic glaciation, now thought to have occurred at 2.6 Ma [Cande and Kent, 1992].

ODP drilling on and near the African continental margin in the subtropics and in the equatorial Atlantic during leg 108 resulted in several good long records of mineral flux to the deep sea. Ruddiman and Janecek [1989] note an increase in dust flux to equatorial sites 662/663 and 664 (Figure 8) beginning about 2.4 Ma, remaining high into the Pleistocene and then declining, possibly in two steps, between 0.75 and 0.50 Ma. Tiedemann et al. [1989] and Ruddiman et al. [1989] observe low dust fluxes 8 to 5 m.y. ago to the subtropical Atlantic in sites 657, 659, and 661. Site 658 from the continental slope seems to have characteristics similar to those of site 397, including very high mineral accumulation rates of 5000–10,000 mg (cm² kyr⁻¹), and may be in part hemipelagic. Important increases in the mineral accumulation rate occur about 4 Ma and 1 Ma at these locations. Changes at about 2.5 Ma include a modest increase in mineral flux and an increase in the amplitude of the fluctuations in the record. Biomarkers in the record of organic carbon accumulation [Stein et al., 1989] in these same cores indicate that the Pliocene transition from a humid to an arid environment occurred between 3.1 and 2.45 Ma. Ruddiman et al. [1989], in examining all these records, noted the increase in African aridity at about 4.0 Ma, 1.5 m.y. prior to the onset of major northern hemisphere glaciation, and suggested a link to southern rather than northern hemisphere climate change.

Bloemendal and deMenocal [1989] examined the spectral content of the magnetic susceptibility proxy of terrigenous sediment abundance in Atlantic equatorial site 661. They showed a noticeable increase in the relative importance of obliquity (41 kyr) power in the record since about 2.4 Ma. Precessional power, which occurs throughout the 3.5-m.y. record, is relatively more important in the time before 2.4 Ma.

Cenozoic Record of Dust Fluxes to the North Pacific Ocean

The earlier work on the mass accumulation rate of eolian minerals to the Pacific basin was based on samples recovered by the Deep Sea Drilling Project. Rea and Janecek [1981b] showed from analysis of samples from DSDP site 463 (Figure 6) that the Cretaceous of the central Pacific, south of the equator, was characterized by declining input of an illite-dominated mineral assemblage from the Cenomanian to the Maastrichtian, ending the Cretaceous with low flux values of 20–40 mg (cm² kyr⁻¹). Those authors noted
the general relationship between declining dust input and rising sea level and suggested that the subaerial exposure of the source regions, or lack thereof, determined the amount of dust available for transport to the ocean. The eolian record from sites 464 and 465 on Hess Rise indicated low dust fluxes to the equatorial and North Pacific since the middle Cretaceous, increasing markedly in the past few million years [Rea and Harrsch, 1981]. A more broadly regional study with emphasis on the late Cenozoic showed that the flux of dust to the North Pacific increased by a factor of 4 or 5 beginning 3.5 m.y. ago [Rea and Janecek, 1982]. The size of the eolian grains increased modestly during the same interval, providing evidence for drier northern hemisphere continents and slightly stronger atmospheric circulation associated with the late Cenozoic northern hemisphere cooling. A secondary maximum in both eolian size and flux occurs about 5 Ma [Rea and Janecek, 1982].

Core LL44-GPC3 from 5705 m depth in the central gyre region of the North Pacific (Figure 6) has provided the best single record of whole Cenozoic atmospheric circulation, continental paleoclimate, and ocean paleochemistry available. GPC3 consists of pelagic clays that accumulated at generally very low rates, such that its 24.3-m record spans about 70 million years without appreciable hiatuses. Corliss and Hollister [1979] first described the core as dominantly eolian in provenance with an upper unit grading downward at 9–12 m below seafloor to an underlying unit of different mineral assemblages. Stratigraphic control was provided for GPC3 from studies of ichthyolith (fish teeth) stratigraphy [Doyle and Riedel, 1979] and of magnetic reversal stratigraphy in the upper 4.3 m of the core [Prince et al., 1980].

Paleoenvironmental interpretations of LL44-GPC3 began with a study of its clay and quartz mineralogy [Leinen and Heath, 1981]. Corliss and Hollister [1982] provided a detailed geological, geotechnical, and geochemical description of the core. Combined with the newly determined stratigraphy, these authors were able to show that a mineralogical transition at a depth of approximately 10–11 m corresponded with geochemical changes and that this transition occurred near the Oligocene-Miocene boundary. Neogene sediments displayed a more detrital nature than the underlying Paleogene materials, as based on quartz and illite abundance [Leinen and Heath, 1981] and on abundance patterns of Al, Si, and the transition metals [Corliss and Hollister, 1982]. Leinen and Heath [1981] noted that the modern mineral assemblage was acquired by 9 Ma and that a large increase in mineral flux occurred about 3 Ma.

Janecek and Rea [1983] extracted the eolian mineral component from LL44-GPC3 and quantified its mass accumulation rate and grain size throughout the Cenozoic (Figure 16). This record was the first long, continuous record of its type and has provided considerable insight into the history of atmospheric circulation in the northern hemisphere. Eolian dust accumulated at low rates of 10–20 mg (cm² kyr)⁻¹ throughout the latest Cretaceous and Paleogene time, roughly doubled at about 25 Ma, and increased through the remainder of the Neogene. About 3 Ma the input of dust to the central North Pacific increased from about 30 to 250 mg (cm² kyr)⁻¹, denoting the drying of east central Asia that occurred in conjunction with the onset of northern hemisphere glaciation in the latter portion of the Pliocene. The flux doubling at about 25 Ma occurs at a depth of 10.5 m in the core, the position of the transition between units noted by all the previous workers. Corliss and Hollister [1979, 1982], Leinen and Heath [1981], and Janecek and Rea [1983] all interpreted this transition in mineralogy, chemistry, and flux as representing the time when the core site migrated north from the regime of the trade winds to that dominated by eolian transport in the westerlies and that the change in composition and flux represents the influence of Asian dust sources in the upper portion of the core. An upcore reduction in grain size is associated with the compositional and flux changes (Figure 16). According to the backtrack plots, this trade winds to westerlies transition would have occurred at a paleolatitude of about 22°-24°N.

The grain size record of wind intensity from GPC3 (Figure 16) provides important information about atmospheric circulation during the Cenozoic. The younger portion of the record shows quite small dust grains characterizing Eocene sediments, a coarsening beginning in the early Oligocene, somewhat finer grains in the late Oligocene and early Miocene, an-
The new, provocative, information from this record indicates the onset of northern hemisphere glaciation. The change in eolian grain size near the time of the Paleocene-Eocene (P-E) boundary represents the most significant change in atmospheric circulation in the entire Cenozoic, an upcore decrease in wind intensity of a factor of perhaps 3 or 4 [Janecek and Rea, 1983]. This observation and its confirming evidence from DSDP site 576, discussed below, remained unexplained for several years.

The ensuring work on GPC3 has all been geochemical in nature. Kadko [1985] examined the trace element geochemistry of the core and was able to subdivide the more detrital upper portion of the core from the more authigenic lower portion. Kyte and Wasson [1986] examined the Paleogene and Cretaceous portion of GPC3 for iridium and were able to identify the Ir spike that denotes the Cretaceous-Tertiary (K-T) boundary at a depth of about 20.5 m. The section from 21 m up to 12 m was sampled closely, and no other iridium anomalies were noted [Kyte and Wasson, 1986]. Leinen [1987] determined the geochemistry of sediments in the core and was able to partition the elemental data into detrital, hydrothermal, hydrogenous, and biogenous components. The relative importance of these end-members varies throughout the core, with the detrital component being most important above 10 m, in the Neogene, and the hydrothermal component most important near 18 m, at the P-E boundary [Leinen, 1987]. Kyte et al. [1993b] performed further geochemical analyses and were able to define eight end-member components, similar to the ones defined by Leinen [1987] but including two eolian end-members. The Neogene and Quaternary eolian end-member has a shalilike composition reflecting a continental source in central and eastern Asia, and the Paleogene and Cretaceous eolian end-member has an andesitic composition suggesting a source from the American continent. Kyte et al. [1993b] also identified an increase in the flux of hydrothermal materials to the location of LL44-GPC3 that occurred at the time of the P-E boundary.

Ocean drilling in the North Pacific during summer 1982 on DSDP leg 86 targeted pelagic clay sites that provided important information regarding the Cenozoic history of eolian deposition. Most of that information comes from site 576 at 32.4°N and a depth of 6218 m [Heath et al., 1985a] (Figure 6). Site 576 has a chronostratigraphy based on the ichthyoliths [Doyle and Reidel, 1985] in the older portion and on magnetic reversal stratigraphy in the younger 5 m.y. [Heath et al., 1985b]. The mineralogy Leinen, 1985] and eolian grain size and mass accumulation rate [Janecek, 1983] data from site 576 (Figure 17) proved to be a near match for those found in core LL44-GPC3 [Rea et al., 1985a] about 4000 km to the east of site 576, a robust confirmation of the regional coherency of the eolian signal preserved in deep-sea sediments. Miller et al. [1987], working on carbonate-rich sediments from site 577 cored at a depth of 2678 m on Shatsky Rise, examined the isotopic and faunal transitions associated with the P-E boundary and the size of the eolian grains there. The were able to show that the large change in the size of eolian grains noted at GPC3 and DSDP 576 occurred exactly at that boundary, in magnetic reversal chron 24R. This work tied the changes first noted by Janecek and Rea [1983] into the global series of events that occurred at the time of the P-E boundary. A record of eolian deposition of much higher resolution than was previously available, one that may be continuous back to the latest Miocene, may be found in the magnetic susceptibility data from ODP site 810 located very near site 577 on Shatsky Rise [Polgreen et al., 1993].

In the last several years, overviews of the eolian investigations in the North Pacific have been presented by Leinen and her coworkers. Rea et al. [1985a] compared the records of GPC3 and DSDP 576...
to give a history of Cenozoic eolian transport and continental aridity as seen in a single latitudinal band that now approximates 30°N. Schramm [1989] examined the mineralogy of four potentially eolian North Pacific sites and noted that the mineralogy of these cores changed in the Miocene, significantly prior to the large flux change about 3 Ma. She concluded that a change in the nature of continental weathering came before the enhanced aridity that occasioned the changes at 3 Ma [Schramm, 1989]. The mineralogy presented by Schramm [1989] is probably a good reflection of what was happening on the Asian continent, but inasmuch as the upper portions of two of the sites studied, DSDP 436 and 578, are hemipelagic in nature and have been influenced by abyssal reworking since at least 2.6 Ma [cf. Leg 145 Scientific Party, 1993], some of the eolian interpretations may be in error. Leinen [1989a] has summarized most of the mineralogical, geochemical, and sedimentological information from the North Pacific pelagic clay province.

The Cenozoic Eolian Record of the Southern Hemisphere

There are several long-time scale records of eolian processes available from the southern hemisphere and all of them derive from cores collected by the Deep Sea Drilling Project and the Ocean Drilling Program. Stein and Robert [1985] examined the mineralogy and accumulation of the mineral component of sediments from the leg 90 sites 588, 590, and 591, which lie roughly 600–1000 km east of Australia (Figure 6). The depositional record at those sites is complicated by current winnowing in the later Cenozoic [Stein and Robert, 1985] and possibly by hemipelagic deposition as well. However, the overall picture of eolian processes presented by these sites indicates, on the basis of both the mineralogy and the flux of the accumulating grains, increasing aridity in an Australian source region beginning in northern Australia about 13 Ma and expanding southward since then. Mineralogical considerations indicate further enhancement of aridity about 3 Ma; interpretations based on mass accumulation rates at these sites are complicated by late Cenozoic current winnowing [Stein and Robert, 1985].

The late Oligocene to Pleistocene history of the southern hemisphere trade winds is based on cores raised from the subtropical South Pacific [Bloomstine and Rea, 1986; Rea and Bloomstine, 1986]. The mass accumulation rate of eolian material is characterized by uniformly very low values, perhaps 1–4 mg (cm² kyr)⁻¹, for the past 25 m.y. (Figure 18), indicating that any potential South American source region was of minimal significance. One important change in the size of eolian grains occurs, an upcore increase of about 1 μ unit that occurs at about 9 Ma (Figure 18). There are no changes in the South Pacific eolian record that corresponds to the onset of northern hemisphere glaciation in the late Pliocene.

Figure 18. Composite section of eolian fluxes and grain size from South Pacific cores DSDP 597 and DSDP 598. Fluxes are generally very low; the two peaks at 8 and 17 to 18 Ma are associated with maxima in hydrothermal activity [Lyle et al., 1987] and may represent input of noneolian, perhaps very fine grained, materials. At about 9 Ma the dust grains become nearly 1 μ unit coarser and remain so for the duration of the Cenozoic.

Any interpretation of the Cenozoic oxygen isotope record of environmental change has an underlying murmur of how much of the signal represents a change in the volume of isotopically light ice piled on continents and how much of the signal represents a change in the temperature of bottom waters. This indication of increased intensity of the southern hemisphere trade winds at about 9 Ma is significant because it happened millions of years after oxygen isotopic indication of enhanced ice volume that occurs at 13.5 Ma in the middle Miocene, and strongly implies that the 13.5 Ma event did not involve polar cooling and a concomitant increase in the pole to equator temperature gradient. It seems more likely that the middle Miocene isotopic event represents an increase in continental ice volume [Rea and Bloomstine, 1986].

Schramm and Leinen [1987] examined the record of eolian quartz isolated from samples of pelagic clay recovered in DSDP site 595 in the western subtropical Pacific. Stratigraphy for that core is provided solely from ichthyoliths [Winfrey et al. 1987] and the K-T boundary occurs at a depth of only 19 m. They indicate that fluxes of mineral material are modest in the late Cretaceous and decline in the Paleocene to low values of 5–10 mg (cm² kyr)⁻¹ that characterize the later Paleogene, Neogene, and Quaternary. Zhou and Kyte [1992] conducted a detailed geochemical analysis on the pelagic clays of nearby DSDP site 596. Their iridium data show the Ir spike associated with the K-T
boundary to lie at a subbottom depth of about 20 m. Using multivariate analysis, Zhou and Kyte [1992] were able to identify six geochemical end-members at site 596, including one detrital-continental end-member. Their data show low accumulation rates for the detrital component, 2–4 mg (cm$^2$ kyr)$^{-1}$, in the late Cretaceous and Paleogene and higher flux rates of 20–40 mg (cm$^2$ kyr)$^{-1}$ in the late Neogene and Quaternary. Zhou and Kyte [1992] were uncertain as to the source of the detrital component, suggesting both Australia and Asia as possibilities.

Krissek and Janecek [1993] analyzed the mineral component of sediments recovered from ODP site 803 on the Ontong-Java Plateau during ODP leg 130 (Figure 6). The Ontong-Java record is a complex picture of the accumulation of minerals from several sources of both continental and volcanic affinity that spans Oligocene to Pleistocene time. A continental mineral assemblage characterized by quartz, illite, and kaolinite-chlorite displays an accumulation history similar to that defined for the North Pacific cores [Rea et al., 1985a], leading Krissek and Janecek [1993] to propose an Asian source for this continental assemblage of minerals that accumulated south of the equator in the western Pacific.

All of the long-timescale information on eolian deposition in the Indian Ocean is based on cores taken on ODP leg 121 to the eastern portion of that ocean, where sites were located on Broken Ridge and Ninetyeast Ridge (Figure 9) [Hovan and Rea, 1991, 1992a]. All of the longer eolian records from the Pacific, with the exception of that of Krissek and Janecek [1993] from the Ontong-Java Plateau, are derived from pelagic clay cores and therefore neither well dated nor directly tied to the most used proxy of global change, the $\delta^{18}$O record. The nearly pure carbonates of the southeastern Indian Ocean allowed us to link the southern hemisphere record of eolian deposition directly to the $\delta^{18}$O record for the first time, providing additional insight into the causes of climate change in the eolian source regions. The very low concentrations of the mineral component in these bright white carbonates, usually less than 1 wt %, meant that the occasional coarse volcanic grain biased the grain size measurements significantly and only the dust accumulation rate determinations are useful as a basis for paleoclimatic interpretation. With the exception of the upper portion of site 757, the entire record presented is from deposition beneath the southern hemisphere westerlies derived from sources in Africa [Hovan and Rea, 1991, 1992a].

The flux of dust to the southern Indian Ocean has been low throughout most of the Cenozoic, ranging between 2 and 10 mg (cm$^2$ kyr)$^{-1}$ (Figure 19). Because
there is evidence that southern Africa has been arid for many millions of years [Seisser, 1978; Lancaster, 1984; Van Zinderen Bakker, 1985], the Indian Ocean dust flux record is interpreted as representing the dry side of the Pye curve (Figure 2) such that declining accumulation rates indicate enhanced aridity of the African source regions. The bit of record that may represent material from Australia, the youngest 10 m.y. of site 757, is interpreted in the same manner. Older site 215, situated in a deep basin just west of Ninetyeast Ridge, contains a section that spans the late Paleocene and the P-E boundary. The combined dust flux record from all sites and the 818O record determined for these cores are shown in Figure 19.

There are three times of change in the dust flux record of African aridity that correspond to important times of global change as evidenced by the oxygen isotope record: changes at the Paleocene-Eocene boundary, at the Eocene-Oligocene boundary, and in the middle Miocene. In each of these instances the change is from greater to lesser dust fluxes, indicating increasing aridity of southern Africa in the early Eocene, at the time of onset of Antarctic glaciation at the Eocene-Oligocene boundary, and the time of rapidly increasing southern hemisphere ice volume in the middle Miocene. The younger two transitions occur within single cores and so are better constrained than the change at the P-E boundary, which is based on a comparison of flux data from different cores. There is not indication of southern hemisphere environmental change at any of the Indian Ocean sites that may be associated with the onset of northern hemisphere glaciation at 2.6 Ma [Hovan and Rea, 1992a].

None of the leg 121 sites recovered a P-E boundary section that was free of volcanic ash and useful for studies of the eolian record. Site 215 (Figure 9), which contains Paleocene carbonates changing upward into pelagic clay, was sampled to construct a southern hemisphere record of the significant changes of that time seen in the North Pacific cores. Results of that effort (Figure 20) [Hovan and Rea, 1992b] demonstrated that the reduction in eolian grain size found in the northern hemisphere also occurs in the southern hemisphere, marking this reduction in atmospheric circulation as a truly global event. I will return to the special nature of the P-E boundary in the following section.

CENOZOIC RECORD OF ATMOSPHERIC CIRCULATION

The major paleoclimatic event of the late Cenozoic is the development of northern hemisphere glaciation in the latter portion of the Pliocene. The eolian record of that event is entirely a northern hemisphere record,
one dominated by indications of drying in both the Asian and African source regions. Asian dust fluxes increased by almost an order of magnitude about 2.6 Ma and blanketed most of the North Pacific. Dust of Asian affinities may have penetrated into the southern hemisphere to the low-latitude southwestern Pacific Ocean. The dust flux record of enhanced African aridity at this time is distinct, but the increase is not nearly as great as that in North Pacific cores. There are indications of increased drying in northwestern Africa beginning in the late Miocene and early Pliocene. Late Pliocene increases in eolian grain size have been shown in sediments downwind from both Africa and Asia, indicating at least a modest increase in the intensity of the transporting winds in these northern hemisphere locations. Maximum size of eolian grains occurs in the latest Pliocene or early Pleistocene in both oceans.

The southern hemisphere sites in both the South Pacific (Rea and Bloomstine, 1986; Rea, 1989) and the southern Indian Ocean (Hovan and Rea, 1992a) show no response in either the aridity-flux signal or the grain size–wind intensity signal to the onset of northern hemisphere glaciation. The great late Cenozoic climatic change seems to have been almost entirely a northern hemisphere event, causing profound changes in the climates of Eurasia, North America, and Africa and more vigorous atmospheric circulation in that hemisphere. The southern hemisphere seems far less affected by the events of 2.6 Ma. No distinct, lasting increase in dust flux or change in the grain size signal occurs then, although other evidence suggests a late Cenozoic drying of the Australian continent (Stein and Robert, 1985; Frakes et al., 1987).

The different behavior of the hemispheres in responding to climatic change is what Flohn has termed hemispherical asymmetry (Flohn, 1978, 1981, 1984). The planetary temperature gradients have been different for each hemisphere in the past as they are different today. Polar cooling 2.6 Ma was a northern hemisphere phenomenon associated with the development of ice caps and eventually the freezing of the Arctic Ocean, the greatly increased ice and snow cover in the high northern latitudes, albedo feedback to enhance cooling, etc. In the southern hemisphere there may have been some increase in ice volume on an already cold Antarctica, but there was little further reduction in temperature and no increase in the intensity of the southern hemisphere zonal winds.

Hemispherical asymmetry should have been at its most extreme when the Earth was characterized by one cold pole. Such times will be characterized by vigorous circulation of the atmosphere, thus probably the sea surface current system too, in the cold hemisphere and relatively sluggish circulation in the warm hemisphere. To the extent that the latitude of the ITCZ is a reflection of the energy balance of the hemispheres, it will be offset far into the warmer hemisphere. The climatic zones of tropical rainfall and subtropical aridity should be similarly offset. This is an important consideration because the paleoposition of the ITCZ may be recorded in proxy data of both atmospheric and sea surface circulation and of continental climate. Today in the Pacific the ITCZ ranges from a few degrees north in northern hemisphere winter to 12°N in northern hemisphere summer (Flohn, 1984; Merrill, 1989b).

It seems likely that during the Oligocene and earlier portions of the Miocene, when the world was characterized by accumulation of ice on Antarctica and the continuing thermal isolation of the south pole and by warm and equable climates in the mid to high latitudes of the northern hemisphere, that hemispherical asymmetry would have been at this most extreme. Under such conditions the latitude of the ITCZ in the Pacific basin would have been well north of its present summer location, perhaps in the vicinity of 15°–20°N.

Given this likelihood, we must reconsider the interpretation of the early Miocene changes in composition and grain size in eolian cores LL44-GPC3 and DSDP 576 (Figures 16 and 17). If the ITCZ lies well north of the equator, it seems unlikely that the trade wind–westerlies boundary would be at the latitude of only 22°–24°N; rather, it should have been somewhere between 40° and 50°N. In the central north Pacific pelagic clay cores, the mineral component of older sediments has an American andesitic affinity and younger materials have an Asian shalike affinity (Kyte et al., 1993b). If Miocene climatology mimics today’s, then all of the northern hemisphere Pacific may have been in the depositional regime of Asian dust. Thus the early Neogene change in lithology in these cores may record the northward passage of the site beneath a significantly offset asymmetric ITCZ. The southern hemisphere trade winds should have been much stronger than those of the northern hemisphere, so this transition should also be marked by a reduction in dust grain size in the younger sediments. This size reduction is exactly what is observed in both cores. Thus it seems plausible that this sedimentary event may define the position of the Pacific mid-Cenozoic ITCZ at its most extreme, somewhat north of 20°N in the latest Oligocene and earliest Miocene, rather than denoting a boundary surprisingly far south between the trade winds and westerlies.

In a recent attempt to characterize hemispherical asymmetry and the history of the ITCZ in the eastern equatorial Pacific, Hovan [1994] examined the eolian record from four ODP cores recovered during leg 138 along 110°W between 3°S and about 7°N, sites 848, 849, 852, and 853 (Figure 6). Today the average position of the ITCZ along the leg 138 transect is at about 5°N. The modern eolian regime at this location is characterized by relatively higher dust fluxes beneath the region of rainout at the ITCZ and relatively smaller grain size because of the reduced wind intensities
there [Raemdonck et al., 1986; Hovan, 1994]. Hovan was able to show in a series of time slices (Figure 21) that this modern pattern has been in place only in the last 4 million years and prior to that time the ITCZ lay to the north of the leg 138 drill sites. The earliest Pliocene southerly migration of the ITCZ is consistent with northern hemisphere cooling then as evidenced by ice-rafted dropstones in lower Pliocene sediments in both the North Pacific and North Atlantic. The depositional pattern at the equator and 110°W does not change in response to the onset of northern hemisphere glaciation, consistent with other proxies dominated by southern hemisphere atmospheric circulation (Figure 21) [Hovan, 1994].

A last point regarding hemispherical asymmetry is the different indications of changing intensity of atmospheric circulation give by the grain size records of each hemisphere. The south Pacific eolian data from the trade wind regime (Figure 18) [Bloomstine and Rea, 1986; Rea and Bloomstine, 1986] show one important change in the size of the eolian grains, a significant coarsening that occurred at approximately 9 Ma. Since then the eolian grain size has been relatively uniform, suggesting that the southern hemisphere reached its present circulatory vigor in the beginning of the late Miocene. The 9 Ma increase in eolian dust size in the southern hemisphere is 4.5 m.y. younger than the indication of enhanced ice volume or of reduced temperature that is given by the oxygen isotope record of global change. We do not have an equivalent

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**Figure 21.** Eight one-million year time slices of eolian grain size and flux along a transect beneath the present ITCZ at 110°W [after Hovan, 1994]. Note that the present pattern of eolian deposition at the ITCZ, characterized by a minimum in grain size and a local maximum in deposition rate, became established at about 5°N roughly 4 million years ago. Prior to 4 Ma, the ITCZ was farther north.
record of the northern hemisphere trade winds. Northern hemisphere westerlies, as seen in the records from LL44-GPC3 and DSDP 576 (Figures 16 and 17), may have been continually increasing their vigor in through the latest Miocene and on into the late Pliocene. In each record the upper couple of samples have somewhat smaller sizes, indicating the possibility of a general decline of circulation intensity in the middle and later part of the Pleistocene.

In all of our studies of the eolian dust record of global climate change, one of the most fundamental and far-reaching discoveries was achieved early on: the documentation of a significant decrease in the intensity of atmospheric circulation that occurs at the Paleocene-Eocene boundary [Janecek and Rea, 1983]. This change is by far the largest in the Cenozoic and has profound implications for sea surface circulation and global heat transport. The marine record of the P-E boundary is marked by the most pronounced extinction-turnover event among benthic foraminifera in the last 90 million years. This extinction event occurs at the end of about 2-my.-long period of transition that has profound implications for sea surface circulation and global heat transport. The marine record of the P-E boundary accompanies the most pronounced extinction-turnover event among benthic foraminifera in the last 90 million years. This extinction event occurs at the end of about 2-my.-long period of transition that includes a 1.0 to 1.5% shift in benthic δ18O toward heavier values, a 3% shift in δ18O toward lighter values, and a decline in the size of eolian grains (Figure 20). These data imply that the early Eocene was characterized by the warmest climate of the Cenozoic, there were greater concentrations of dissolved organic carbon in the ocean, and atmospheric and sea surface circulation was sluggish. Worldwide plate boundary reorganizations occur beginning at the P-E boundary accompanied by a global increase in both volcanism and seafloor hydrothermal activity. On land the mammals underwent their major evolutionary radiation at this same time [Owen and Rea, 1985; Rea et al., 1990; Hovan and Rea, 1992b]. A much more rapid climatic excursion is superimposed on this longer-duration transition [Kennett and Stott, 1991].

We have linked all these phenomena by suggesting that the tectono-volcanic events of the late Paleocene and early Eocene served to increase the amount of CO2 in the atmosphere by subaerial volcanism and greatly enhanced seafloor hydrothermal activity [Owen and Rea, 1985]. Raised levels of CO2 resulted in the shift to warm climates as reflected by the oxygen isotope data. Increased evaporation and runoff brought newly eroded organic carbon into the ocean, causing the whole-ocean shift in carbon isotopes, and atmospheric circulation slowed in response to the broad-scale global warming. Benthic foraminifers were unable to survive the new conditions, which may include warmer water and reduced organic carbon rain, and so many became extinct [Rea et al., 1990].

There is a particular and unresolved problem with regard to the paleoclimatic and paleoceanographic transition that occurred at the P-E boundary. Covey and Barron [1988] observed that if there is a certain amount of heat to be transported from equator to pole to maintain the global energy balance, then if the atmosphere slows and transports less heat, the ocean must compensate and transport relatively more heat. A further observation is that during the warm early Eocene, the polar to equator temperature gradients were much less steep than they are now [Barron, 1987], implying relatively more warming in higher latitudes. This observation entails two consequences. First, since elevated partial pressure of CO2 warms all parts of the planet equally, there must be more than mere CO2 warming going on [Sloan et al., 1992]. Second, reduced temperature gradients require relatively greater rates of latitudinal heat transport. The exact mechanism for this heat transport, which must have been accomplished by the ocean, is not yet quantified and may have to await the development of coupled ocean-atmosphere circulation models.

The many events of the P-E boundary present problems critical to the understanding and interpretation of global environmental change. The atmosphere is an important component of these changes, and we can not understand the changes in surface and deepwater circulation in the ocean or in the climatic regime of the continents in the absence of information about atmospheric circulation. These questions that incorporate all components of the Earth's climatic system are broad and interdisciplinary, and their resolution requires interaction between those who generate proxy data of climate change and those who construct computer models of past climates [Sloan and Barron, 1992].

Summary

Eolian dust preserved in deep-sea sediments is the only direct proxy indicator suitable for the reconstruction of the geologic history of wind. Quantification of the mineral grains and their mass accumulation rate provides information both on the climate of the eolian source region and on the intensity of the transporting zonal winds. Composition of the dust provides provenance information.

Dust is lifted from semiarid regions of continents by strong spring storms and transported by the zonal winds for long distances in the upper troposphere. Currently, there are three major sources of dust to the deep sea: eastern Asia, northwestern Africa, and Arabia. All three are in the northern hemisphere, which as a result is 1 to 2 orders of magnitude more dusty than the southern hemisphere. Annual dust loading as determined by the atmospheric scientists is thought to be about 5% of that of rivers and is estimated to be in the range of 6–9 × 10^14 g yr⁻¹ [Prospero, 1981b; Duce et al., 1991]. This value, when converted into the flux values used by marine geologists, is of the order of 200–250 mg (cm² kyr⁻¹) for the whole ocean. Maps constructed from all the dust flux values available in
the literature show that the value of 250 mg (cm² kyr⁻¹) is exceeded only downwind from the important source regions and, for the whole ocean, is high by a factor of 4 or 5. The entire southern hemisphere with the exception of a small region southwest of Australia and New Zealand is characterized by very low dust inputs, only a few mg (cm² kyr⁻¹). Either most of the dust transported to the ocean is deposited in the zone of hemipelagic sedimentation and is "lost" to further detection, or the dust loading estimates of the atmospheric scientists are very high. If anything, the modern dust loading estimates shown in Figure 11 would be biased toward greater values by mankind’s use of the planet and therefore higher than the long-term averages determined from the sedimentology. The general agreement between the sedimentary record as presented in Figures 7, 8, and 9 and the mineral aerosol information from Duce et al. [1991] (Figure 11) suggests that the total dust loading estimate of 6–9 × 10¹⁴ g yr⁻¹ is too high and should be lowered to 1–3 × 10¹⁴ g yr⁻¹.

Records of continental source region climate demonstrate considerable variation on both orbital and tectonic time scales. Most of the northern hemisphere is drier during glacial times and more humid during interglacials [Hovan and Rea, 1989, 1991; Clemens and Prell, 1990, 1991a; deMenocal et al., 1993]. The amount of dust transported in the northern hemisphere during glacial times may have increased by a factor of 3–5 over the present transport conditions. Northwestern South America varies in the opposite sense, being more humid during glacials and drier during interglacials [Chuey et al., 1987; Rea, 1990]; less material is brought west to the equatorial Pacific south of the ITCZ during glacial times than during interglacials.

Both the dust flux and the eolian grain size records contain significant amounts of their paleoclimatic signal at the Milankovitch periodicities of orbital variability (Table 1). As a generalization, there is more 100-kyr power in the flux records of source area climate and relatively more shorter-period variability at time scales of obliquity and precession in the dust grain size signal of wind intensity. A combination tone with a period of 30–35 kyr is present in many records of wind transport and is the dominant forcing in records from the equatorial Pacific [Fistas and Rea, 1988]. The nature of variability of eolian and other paleoclimatic proxy records changes in middle Brunhes time (the mid-Brunhes climate event [Jansen et al., 1986; Rea, 1990]). Longer records of orbital variability of eolian processes demonstrate a pronounced increase in the importance of 41-kyr power associated with the onset of northern hemisphere glaciation [Bloemendal and deMenocal, 1989].

Results of these spectral analyses show that eolian flux and eolian grain size do not respond to the same climate forcing parameters. The observation that dust flux varies on the longer time scales of glacial to interglacial stages and that the dust grain size varies on shorter time scales emphasizes an important aspect of the eolian paleoclimatic record. These two signals are independent (Figure 4). Dust flux is not related to wind intensity, and it is incorrect to assume that glacial stages have uniformly stronger winds.

The overwhelming event in the Cenozoic record of dust accumulation is the five- to tenfold increase in flux that occurred in the North Pacific in conjunction with the onset of northern hemisphere glaciation [Rea et al., 1985a]. Dust fluxes also increased downwind from the Sahara at this time [Ruddiman and Janecek, 1989; Ruddiman et al., 1989]. A modest increase in eolian grain size accompanied these late Pliocene flux changes, indicating that the northern hemisphere became drier and the zonal winds became stronger then. In contrast, the several southern hemisphere records show no response in either the flux of dust to the seafloor or in the size of the dust grains to the big changes happening in the northern hemisphere. Southern hemisphere dust fluxes have been very low throughout the Cenozoic, with the possible exception of the Paleocene [Rea and Bloomstine, 1986; Hovan and Rea, 1992a].

The lack of response of southern hemisphere atmospheric circulation to a large change in northern hemisphere climate is a good example of hemispherical asymmetry, the concept of independent circulatory behavior of each hemisphere [Flohn, 1981]. Such asymmetry would be strongest when the Earth is characterized by one cold pole and one warm pole. As a result of the circulation energy being much stronger in the colder hemisphere, the position of the Intertropical Convergence Zone is offset well into the warmer hemisphere. The Cenozoic temperature asymmetry began with the buildup of ice on Antarctica about 35 Ma and remained high until the cooling of the northern hemisphere beginning in the late Miocene and culminating in significant northern hemisphere glaciation 2.6 Ma. Today the pole to equator temperature gradient is equal at both hemispheres in northern hemisphere winter but 27° more to the south than the north during southern hemisphere winter [Flohn, 1981]. In response, the latitudinal position of the ITCZ migrates to 12°N in the northern hemisphere summer. The record of 32 million years of hemispherical asymmetry should be observable in paleoclimatic records. Our data are consistent with the ITCZ’s having been as far north as 22°N in the central Pacific 25 m.y. ago and show that it migrated south to its present location in the eastern equatorial Pacific about 4 Ma [Hovan, 1994].

The single largest change in atmospheric circulation in the Cenozoic was a severalfold reduction in wind intensity that occurred at the Paleocene-Eocene boundary. This event is part of a series of environmental changes that occurred then and may be a direct response to an increase in the ability of the ocean to effect latitudinal heat transport.
SUGGESTIONS FOR FUTURE STUDIES

As with any proxy indicator of past environmental conditions, our knowledge of eolian paleoclimatology could be improved in important ways by learning more about modern transport processes, how the mineral aerosol records those processes, and the geologic history of those processes. The finding that the global dust flux patterns indicate much lower amounts of transport to and deposition in the oceans than had been estimated suggests that there is more to learn about dust generation, transport, and rainout and dryfall processes and how the different flux estimates are made.

A quantification of zonal wind speeds based on the size distribution of the eolian grains would be a significant contribution to these kinds of studies. Perhaps an empirical approach to these questions involving grain size analysis of aerosols collected in the middle and upper troposphere would be useful. There should be a distinct kind of information present in the nature of the giant grains, possibly information regarding the energetics of individual large dust storms. Computer models of greenhouse warming suggest that warmer climates may be characterized by stronger storms; understanding giant grains may allow pursuit of this sort of topic in the paleorecord.

There are some obvious prerequisites to a fuller understanding of the paleoclimatic record provided by the eolian dust preserved in sediments and ice cores. We have not yet been able to characterize, with satisfactory orbital time scale resolution, the Quaternary history of the major zonal wind belts. Present grain size data monitor the northern hemisphere westerlies, the southern hemisphere trade winds, and the Indian Ocean monsoons. Good data on all wind systems from each ocean are needed to provide a complete picture of this important aspect of earth system history. The more or less direct forcing of climate by the primary periods of the orbital cycles is becoming relatively well understood, but why important amounts of variance occur at the combination periodicities of about 30 to 35 kyr is not well understood. These periodicities are an important aspect of the geologic history of wind and need further elucidation.

Provenance studies are important, not so much for understanding the modern transport systems, but to allow better interpretation of the paleoclimatic record. As core sites drift with the plates across zonal wind boundaries, that resulting change in continental source regions will be caught in the mineralogical or geochemical records of provenance. Provenance information is particularly important to the full understanding of ice core particulate records. Further studies of ice core particulates should include MAR values for the mineral aerosol, separate from the volcanic particles, and grain size data. Determining the eolian record in pelagic cores near ice caps would help in the interpretation of the ice core dust data. Sedimentological realties suggest that this goal may be achievable in the southern ocean but difficult in the North Atlantic.

Studies on longer, tectonic time scales need to be continued, particularly in the southern hemisphere where further documentation of the changes at the P-E boundary is needed. Indications of a pronounced hemispherical asymmetry through much of the Cenozoic entail implications for ocean circulation and continental climatic zonations that may be testable. Finally, these very different climatic scenarios suggested by the eolian paleoclimatic research form a natural point of interaction with the community of scientists who use general circulation models to understand past climates and coming climate changes. This potential interaction between those who generate proxy data of past climatic conditions and those who attempt to quantify those conditions in computer models is critically important to the goal of achieving a full understanding of the causes and consequences of climate change.

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