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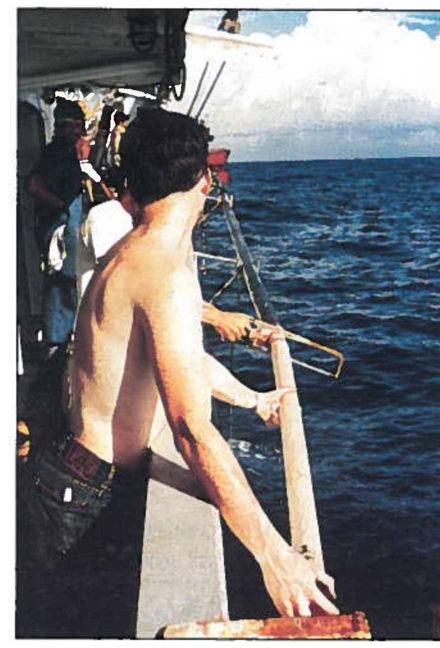
INSIDE

Geologic Records in Deep Sea Muds

David K. Rea
Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1063



Sectioning a piston core aboard the R/V *Yaquina.*

Bringing core aboard the Glomar *Challenger.*

ABSTRACT

The geologic record of the muds and clays of the deep sea contains information regarding uplift within and climate of the continental source region for those sediments and, to a lesser extent, of changes in sea level. Detailing the terrigenous sedimentary record in a hemipelagic or pelagic core is the only way in which the climatic histories of the land and sea can be compared directly. The history of the mass accumulation rate of terrigenous sediments is the starting point for discussions of global mass balances and, together with other information, permits definition of when chemical and physical weathering processes were important during the Cenozoic. Significant chemical weathering began at the Eocene-Oligocene boundary and continued for at least 20 m.y. before physical weathering became dominant in the middle or late Miocene.

INTRODUCTION

Ninety-five percent of the terrigenous material entering the ocean is delivered by rivers, and most of it is deposited on or near the continental margin. A minor amount bypasses the continental margin and is deposited, by a variety of processes, in the deep ocean. In the past decade marine geologists have become proficient at reading the multifaceted record offered by the accumulation of terrigenous materials in hemipelagic and pelagic environments. They have found that this record can be applied widely to questions of broad geological importance. In this overview, examples of the kind of research now being carried out in this area illustrate the different geological topics that are amenable to investigation by studies of the record of terrigenous sediment in the deep sea.

The deposition of terrigenous sediment in the deep sea is controlled by a combination of mountain uplift, climate of the sedimentary source region, and sea level. Signals of these three may be fully integrated in the core-record we recover from the sea floor, but commonly one of them clearly predominates and provides insight into geologic process or history. Uplift of the source region can result in an order of magnitude or greater signal in the accumulation rate of the mineral component of deep-sea sediments. The distal view of uplift of a major mountain range thus obtained integrates over subcontinental-sized drainage basins and is capable of providing a holistic overview of important tectonic events. The climate of the continental source region is commonly the dominant control of marine sedimentation. Input of river-derived hemipelagic mud responds to the degree of physical erosion in, relative humidity of, and runoff from the drainage basin. The flux of eolian dust to the deep sea is a record of the relative aridity of the eolian source region. Ice-rafted debris (IRD) indicates the presence of glaciers at sea level. Further, characterization of the continental record of global climate change from proxy records in pelagic sediment usually provides an opportunity to link the land record to the oceanographic record determined from the same core. Linking the land and sea records of climate change has been an important goal of the paleoclimate community for years. There is no better way to discover the interactive behavior among all parts of Earth's climatic system. The past 15 years have provided a clear demonstration of how changes in sea level control the deposition of sedimentary units or packages on continental margins. In general, highstands are times of deposition on continental shelves, and during lowstands more material is transported directly to the continental slope and sea floor. The distal, deep-sea record of this process is not well defined as yet, but it should be present in the form of either bottom-process-related sediments, such as turbidites, or in the mass accumulation rate of hemipelagic sediment. Finally, the history of the mass flux of particulates from the continents to the oceans provides a constraint for conceptual and computational models of geochemists pondering global cycles of elements and the oceanic aspect of such cycles.

Below I present brief summaries of current research involving aspects of terrigenous deposition. New information is available regarding important topics such as linking marine and continental records of climate change, uplift history of the Himalayas, and the times of chemical vs. physical weathering of continents. Older results like the major change in atmospheric circulation at the Paleocene-Eocene boundary or the paleoclimatic record provided by ice-rafted debris have stimulated new avenues of research.

PROCESSES OF TERRIGENOUS SEDIMENTATION

The general process of downslope mass movement of sediment as gravity flows of one category or another has been the subject of considerable research in sedimentology during the past several decades (Pickering et al., 1989) and will not be considered further here. It has been about two decades since marine geologists have become aware of how active a place the deep sea floor is, and that much of the sediment reaching the lower part of the continental slope or rise is redistributed by abyssal currents. These processes are particularly important in the Atlantic where both the southward-flowing North Atlantic Deep Water and the northward-flowing Antarctic Bottom Water redistribute abyssal sediments (e.g., Poag and de Graciansky, 1992), forming a variety of current-mediated deposits. Only when the sediment supply overwhelms the capacity of oceanic circulation to redistribute material along the continental margin do deposits such as the Mississippi Delta or the Amazon Cone or the Bengal Fan form.

Hemipelagic deposits consist of fine-grained, silt and clay-sized muds deposited within hundreds of kilometres 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 sea floor adjacent to the continents. The horizontal advection of lithogenous material has been well documented by sediment trap studies which have shown that this process is the dominant one of terrigenous sedimentation up to hundreds of kilometres offshore (Honjo et al., 1982; Heggie et al., 1987; Saito et al., 1992). These deep-sea muds are the least well known of all abyssal sediments, partly because they have been difficult to date and partly because their paleoenvironmental interpretation has not always been obvious. Both fluvial supply and sea level should exert a control on the mass accumulation rate of fine-grained hemipelagic mud in the deep sea, and these two determinants may often work in concert.

Calved bergs from glaciers reaching the ocean carry poorly sorted sedimentary debris far out to sea. The most obvious of these materials are dropstones, which are present in all high-latitude sediments during glacial times. Finer grained materials are also ice rafted along with the pebbles and provide insight into the details of high-latitude climatic and oceanographic processes.

Seaward of the regions characterized by hemipelagic deposition, away from the influence of turbidites and redistributional processes, and equatorward of the influence of ice rafting, the mineral component of deep-sea pelagic clays is dominated by eolian dust (Win-

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dom, 1975). Dust is transported to the ocean by a few powerful spring storms that raise material from arid and semi-arid regions. The coarse fraction settles out of the air quickly, and the fine material travels long distances in the upper troposphere and is eventually deposited by both dryfall and washout processes. Dust in the deep sea provides a record of the aridity of the continental source region in its accumulation rate (Prospero, 1981; Prospero et al., 1983; Rea et al., 1985) and a record of the intensity of the transporting winds in its grain size (Janecek and Rea, 1985; Rea et al., 1985). Eolian flux and grain-size records vary independently.

RATES OF SEDIMENT DEPOSITION

Every component of a deep-sea sediment, whether biogenic, terrigenous, or even authigenic, accumulates in response to a different combination of physical, biological, and chemical processes. No component accumulates at a constant rate. Consideration of abundance percentage, a standard mode of investigation, provides some useful information about the dominant sediment component, but all minor components fluctuate in abundance in response to, and antithetically from, the major component. To determine the input history of any sedimentary component, it is necessary to determine the mass accumulation rate (MAR), or flux, of that component. Sediment MAR is measured in units of mass per unit area and time, commonly $g \bullet cm^{-2} \bullet ka^{-1}$, and is the product of the linear sedimentation rate in cm/ka and the dry bulk density in g/cm^3. Incorporation of the bulk density term into the MAR accounts for the compaction and dewatering that occur with time and sediment loading; thus, MAR values are directly comparable for sediments of all ages and burial depths. Furthermore, because they are true mass-flux measurements, MAR values are the appropriate starting point for any mass-balance calculations. The MAR of any one sediment component is the product of the total MAR and the percent abundance of that component. Some typical MAR values for terrigenous sediments are tens of $g \bullet cm^{-2} \bullet ka^{-1}$ for turbidites, 0.5 to 2 or 3 $g \bullet cm^{-2} \bullet ka^{-1}$ for hemipelagic muds, and a few to hundreds of $mg \bullet cm^{-2} \bullet ka^{-1}$ for eolian dust. It is these flux values, along with compositional and grain size information, that provide the Earth history signal in the terrigenous sediments of the deep sea.

SOME EXAMPLES OF THE RECORD CONTAINED IN DEEP-SEA MUDS

Among the several objectives of the Ocean Drilling Program (ODP) nine-leg effort in the Indian Ocean (Duncan et al., 1992) was to determine the uplift history of the Himalayas by studying the clastic material shed from them. In accomplishing this task, different investigators studied the composition (Yokoyama et al., 1990; Brass and Raman, 1990; Amano and Taira, 1992) and the sediment mass accumulation rate history (Rea, 1992) of the terrigenous deposits of the northern Indian Ocean. I combined the sediment flux calculations from eleven suitable sites into one stacked, averaged, and normalized record (Rea 1992; Fig. 1), which provides a clear picture of the geologic history of this process. There are two main pulses of sedimentation, one in the late Miocene, between 9 and 6 Ma, and one in the Pliocene, between 4 and 2 Ma. Lesser flux maxima occur at 0 to 1 and 10.5 to 11.5 Ma. Studies of the mineralogy of the Bengal Fan turbidites show that the two main sediment pulses are uniquely characterized by minerals derived from erosion of the metamorphic core of the Higher Himalayas (Brass and Raman, 1990; Amano and Taira, 1992). These marine data are in agreement with similar information from a more proximal setting; the sedimentation rate and mineralogy of the Siwalik deposits of Pakistan show the same temporal correspondence of metamorphic minerals and high flux rates (Johnson et al., 1985). The results all point to significant uplift of the Himalayas occurring in two distinct phases beginning in the late Miocene (Rea, 1992; Fig. 1).

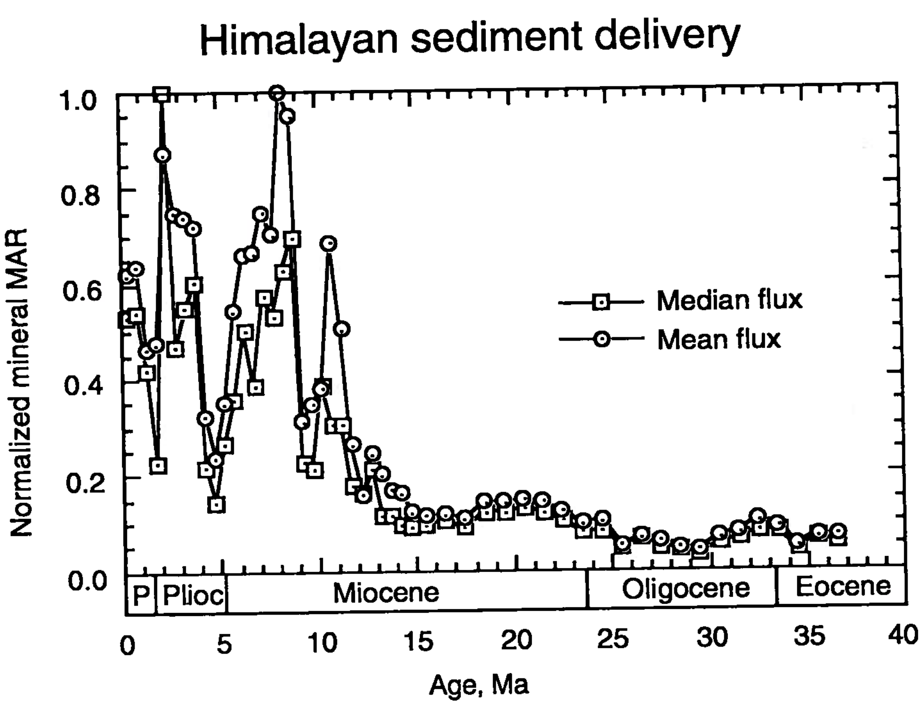

Figure 1. Normalized mass accumulation rate (MAR) of terrigenous sediment at 11 ODP and DSDP drill sites in the northern Indian Ocean. Data are from Rea (1992).

In the northwestern Atlantic, the major Cenozoic pulse of siliciclastic deposition occurred in the middle Miocene, and rates continued to be high through the remainder of the Cenozoic. The Miocene pulse is thought to represent uplift in the central Appalachian source region; the Pliocene-Pleistocene high rates are most likely related to the glaciation of eastern North America (Poag, 1992).

The study of terrigenous deposition in the northern Indian Ocean (Rea, 1992) provided two insights that will be useful in future efforts. First, three sites drilled within 10 km of each other on the Bengal Fan all show similar sediment flux patterns, indicating that the problem of local variability in such deposits is much less than previously thought (Cochran, 1990). Second, the temporal flux patterns of the six turbidite records are as a group no different than the flux patterns of the five hemipelagic cores, although the amounts differ by an order of magnitude or more (Rea, 1992). This last is a particularly important point because it means that hemipelagic sites can be reliable recorders of the sediment input history of entire ocean basins; it is a critical observation because complete recovery of a hemipelagic sedimentary section is far more likely than even adequate recovery of a turbidite section.

Source-region climate exerts a significant control on the deposition of various kinds of terrigenous sediments. The clearest indication of glaciation is the presence of IRD in pelagic sediments. After a century and a half of discussion and controversy regarding the nature and timing of Northern Hemisphere glaciation, the time of the onset of significant continental ice accumulation was finally resolved by examination of the record of IRD in the North Atlantic (Shackleton et al., 1984a) and North Pacific (Rea and Schrader, 1985). These studies showed simultaneous beginning of significant IRD input at the time of the Matuyama-Gauss magnetic reversal, now thought to be 2.6 Ma (Cande and Kent, 1992). Similar studies conducted more recently in the Southern Ocean confirm the timing of the onset of Antarctic glaciation in the latest Eocene and earliest Oligocene (Barron et al., 1991; Zachos et al., 1992). Higher resolution studies of ice rafting reveal details of glacial-interglacial processes (Ruddiman, 1977; Krissek et al., 1985).

In regions and on shorter glacial-interglacial (or orbital) time scales where differential uplift does not dominate sediment delivery, the MAR of hemipelagic muds is determined by some combination of sea-level change and continental runoff. To my knowledge, no one has tried to distinguish between these two signals in a single hemipelagic core. Only a few hemipelagic cores have good data on mass accumulation rate. Two lie just west of South America, V19-29 at lat 3.6°S, about 250 km offshore from the mouth of the Guayaquil River of Ecuador, and Y71-6-12 at 16.4°S, 300 km offshore from southern Peru. The paleoclimatology of the northern Andes is adequately known and is a history of full lakes and moist climates during glacial times and dry lakes and salars during interglacial times, like now (cf. Van der Hammen, 1985). The Pacific margin of northern South America is quite narrow and is the site of modest sediment deposition at most; thus, the effects of sea-level change on deep-sea sedimentation, especially seaward of the trench, may be less there than elsewhere. The mineral flux data from both of these cores (Fig. 2; Molina-Cruz, 1977) show maxima are associated with glacial stages 2 and 4, and minima associated with interglacial stages 1, 3, and 5, values that are consistent with Andean runoff determining the flux of hemipelagic sediments to the easternmost South Pacific.

Results of two studies in the North Pacific are clear examples of the sort of paleoclimate information that the eolian component of pelagic sediments may provide. The first project of this type we undertook was to define the whole-Cenozoic record of eolian input in order to discover the history of continental climate change and of the intensity of atmospheric circulation (Janecek and Rea, 1983; Rea et al., 1985). That study showed that the single large event in dust flux is an order of magnitude increase that occurred in Pliocene time and reflects the drying of the China-Gobi eolian source area (Fig. 3). The surprising result of that work is contained in the record of eolian grain size. The middle to late Cenozoic record of eolian grain size is suggestive of ever-increasing intensity of atmospheric circulation, the expected phenomenon associated with the history of high-latitude cooling. The new information here is the Paleocene and latest Cretaceous part of this record which indicates atmospheric circulation more vigorous than that of the late Cenozoic glacial ages. The sudden reduction in grain size (Fig. 3) has since been shown to have occurred exactly at the Paleocene-Eocene boundary in both hemispheres and was apparently a

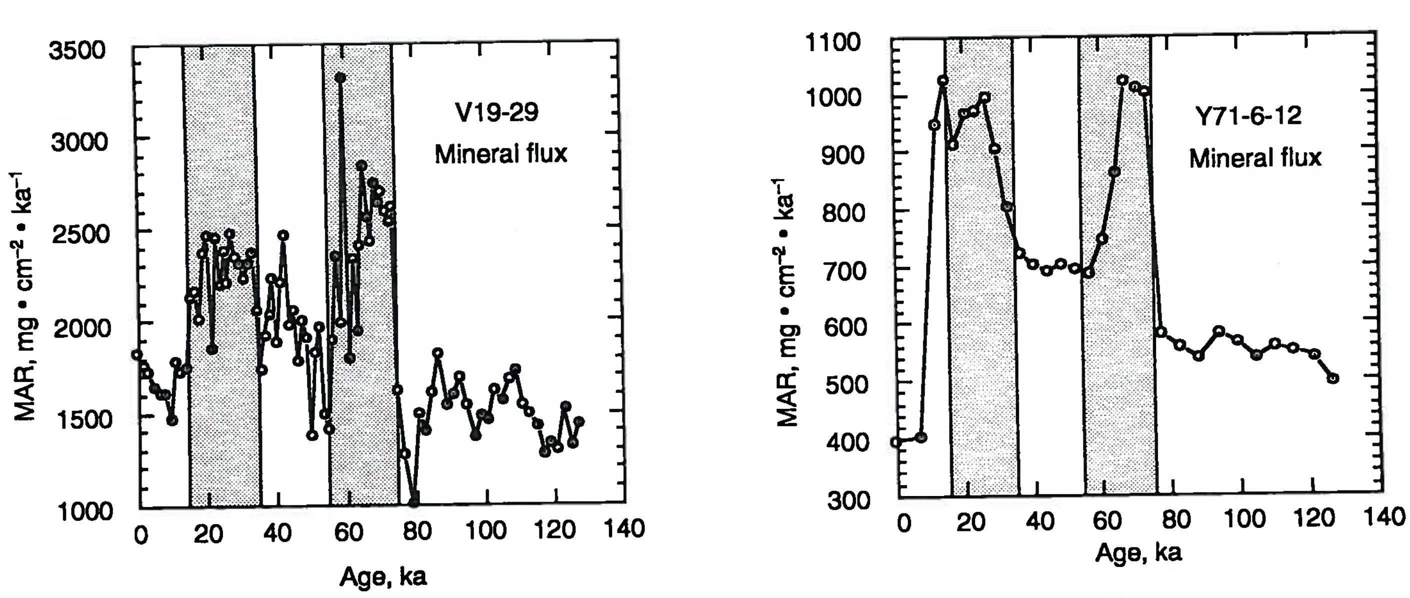

Figure 2. Mass accumulation rate (MAR) of the hemipelagic component of deep-sea sediments in two cores west of South America. See text for locations. Flux maxima at about 15 to 35 ka and 55 to 75 ka (shaded) correspond approximately in time to glacial stages 2 and 4, respectively. Data are from Molina-Cruz (1977).

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global event (Rea et al., 1985, 1990; Hovan and Rea, 1992). We now interpret this sudden reduction in the intensity of atmospheric circulation as reflecting an abrupt increase in the ability of the ocean to transport heat. The several world-wide changes that occurred at the Paleocene-Eocene boundary, such as the extinction of benthic foraminifers, evolutionary radiation of mammals, large excursions in oceanic $\delta^{18}O$ and $\delta^{13}C$, and important changes in both atmospheric and oceanic circulation, are not fully understood and are the subject of continuing research (Miller et al., 1987; Rea et al., 1990; Kennett and Stott, 1991; Hovan and Rea, 1992; Sloan et al., 1992).

A second example of the paleoclimatic information contained in records of eolian deposition is also a good example of the next important aspect of these studies of terrigenous deposition in the deep sea: such records also provide the only linkage between proxy indicators of continental changes (the mineral component) and indicators of oceanic change commonly found in pelagic cores. Details of dust deposition during the past 500 ka in the Northwest Pacific provide an oceanic record of the vast loess deposits of China, one of the classic Quaternary terrestrial sequences (Fig. 4; Hovan et al., 1989, 1991). There, dust flux maxima correspond to the known loess horizons, and minima correspond to the soil interlayers. Determination of this record in a pelagic carbonate-bearing core enables us to tie the China loess record directly to the marine oxygen-isotopic record of global change (Fig. 4). Hovan et al. (1989, 1991) were able to use the results from this core with good terrestrial and marine records to refine the dating of the loess horizons and to show that the loess deposition is in phase with orbitally induced changes in ice volume.

Other examples of linkage between land and sea records of global change include the South American runoff records in East Pacific hemipelagic, carbonate-bearing cores (Fig. 2). For the northern Indian Ocean Prell et al. (1992) defined the history of the monsoons on the basis of proxy indicators of upwelling and atmospheric circulation in deep-sea sediments. One can compare the records of Prell et al. (1992) to the uplift history of the Himalayas depicted in the sediment fluxes shown in Figure 1 and see that monsoons became important in the late Miocene. Because without the mountains the monsoons would be minimal, the temporal correlation of these events is taken to reflect cause and effect (Prell et al., 1992; Rea, 1992).

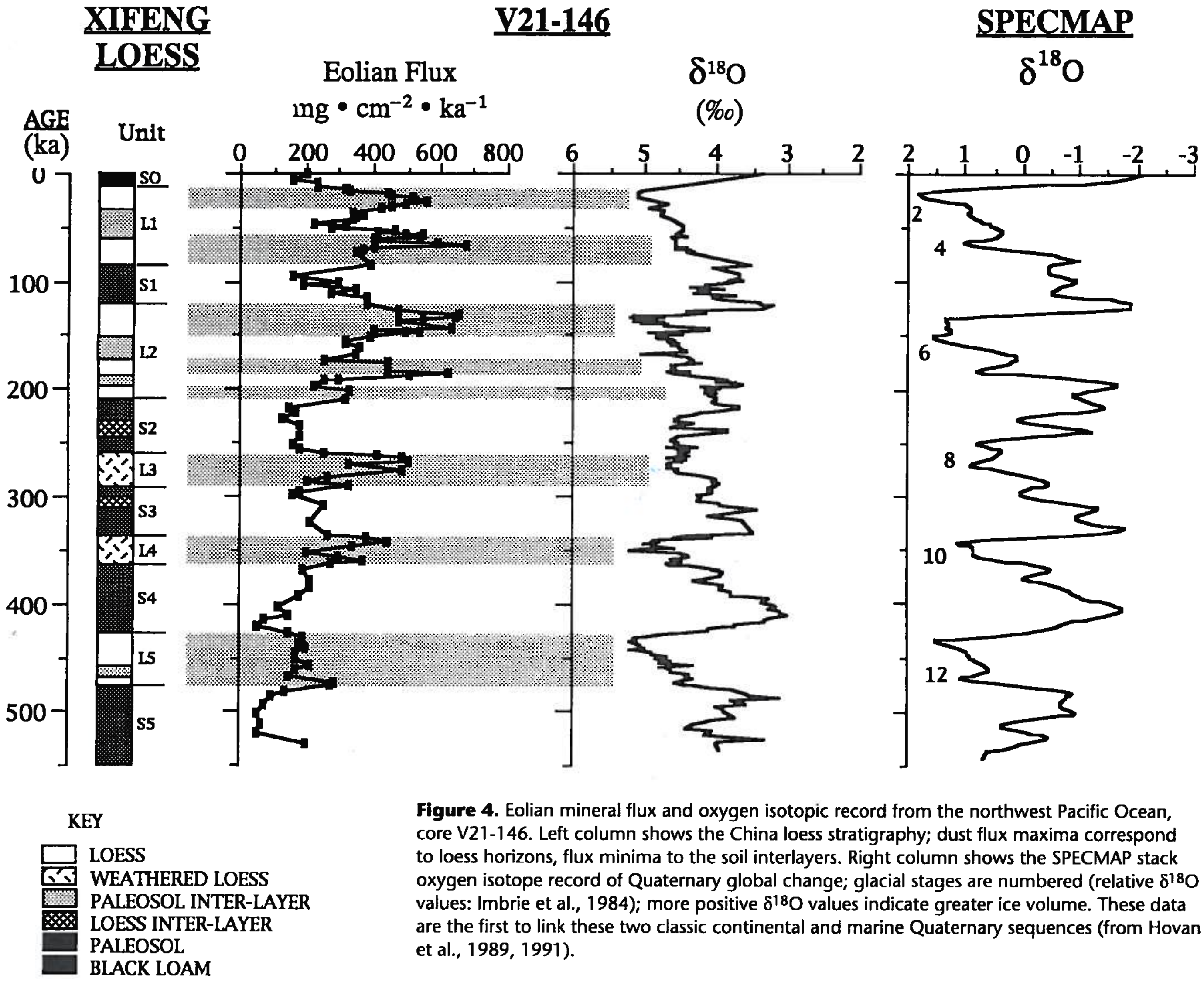

Figure 4. Eolian mineral flux and oxygen isotopic record from the northwest Pacific Ocean, core V21-146. Left column shows the China loess stratigraphy; dust flux maxima correspond to loess horizons, flux minima to the soil interlayers. Right column shows the SPECMAP stack oxygen isotope record of Quaternary global change; glacial stages are numbered (relative $\delta^{18}O$ values: Imbrie et al., 1984); more positive $\delta^{18}O$ values indicate greater ice volume. These data are the first to link these two classic continental and marine Quaternary sequences (from Hovan et al., 1989, 1991).

Despite the clear suggestion that times of lowered sea level should be times of enhanced sediment deposition in the deep sea, the few records we have of Cenozoic siliciclastic accumulation seem to be dominated by either tectonic or climatic events. Records from the northern Indian Ocean (Rea, 1992), the western North Atlantic (Poag, 1992), and an older record from the South Atlantic (Shackleton et al., 1984b) do not show a depositional pattern reminiscent of the Cenozoic sea-level curve (Haq et al., 1987). Particularly, the mid-Oligocene severe drop in sea level does not appear in any of these records. Admittedly, three records provide only a very preliminary view of this history, but from them it seems that sea-level change causes only a second-order effect on terrigenous deposition rates in the deep ocean.

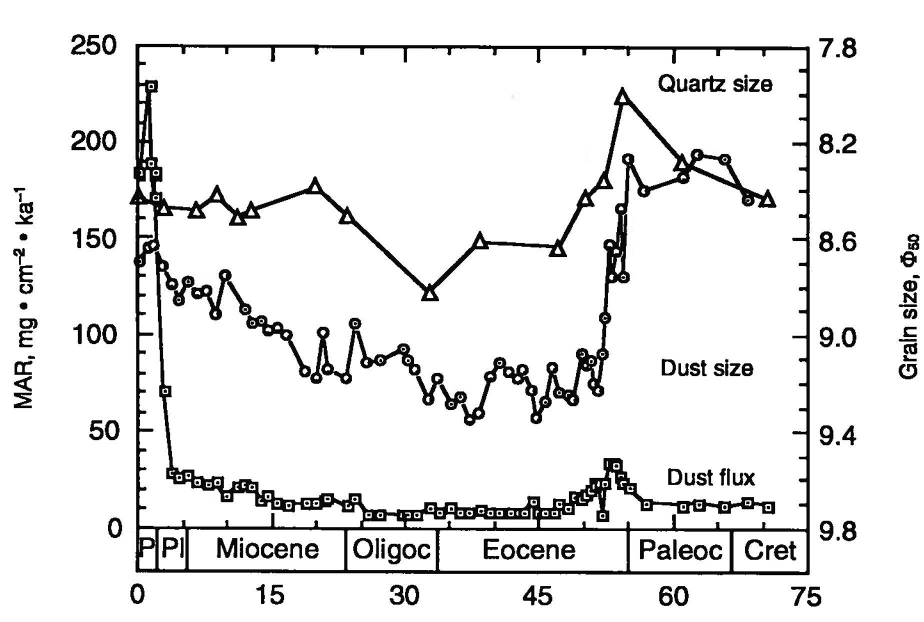

Figure 3. Cenozoic eolian record from the central North Pacific, core LL44-GPC3, showing flux and grain size of the eolian mineral component and size of the isolated quartz grains. Notice the large flux increase at ca. 3 Ma and the large reduction in grain size at ca. 55 Ma. Data are from Janecek and Rea (1983).

Finally, the history of terrigenous sedimentation in the deep sea provides useful constraints to our hypotheses of global geochemical cycles (Fig. 5). Two important aspects of Cenozoic ocean paleochemistry make good examples here. First is the level of the calcite compensation depth (CCD), which denotes that depth where the dissolution rate of $CaCO_3$ matches the sea-surface production rate and below which no calcite is deposited. The deeper the CCD, the more $CaCO_3$ is deposited in the ocean. The largest Cenozoic change in the CCD is a rapid deepening at the Eocene-Oligocene boundary (van Andel, 1975). The isotopic composition of seawater strontium has become increasingly radiogenic since the Paleogene; the steepest part of this curve, indicating the most rapid input of radiogenic strontium (derived from granitic rock) to the ocean, begins at the Eocene-Oligocene boundary and ends in middle Miocene deposits (Hess et al., 1986). These paleochemical changes, the deepening of the CCD, and the onset of radiogenic Sr input have been interpreted as reflecting greatly enhanced input of Ca and of radiogenic Sr to the ocean starting at the Eocene-Oligocene boundary. Climatic deterioration corresponding to the formation of ice on Antarctica has been thought to be the general cause for enhanced weathering and erosion necessary to change the Ca and Sr budgets so dramatically.

Comparison of these records to that of terrigenous input shows that the rapid mid-Cenozoic changes in ocean chemistry were not accompanied by significant siliciclastic deposition. Together, these data suggest four stages of weathering-erosion and concomitant input to the oceans (Fig. 5): (1) Paleocene and Eocene, characterized by low particulate and dissolved fluxes to the ocean; (2) Oligocene to middle Miocene, characterized by important dissolved fluxes but low particulate fluxes, denoting the predominance of chemical weathering of relatively low-lying continents; (3) middle Miocene to late Pliocene, when particulate fluxes predominated over dissolved in a time of broad uplifts; and (4) late Pliocene to present, characterized by significant dissolved and particulate fluxes, mostly as a result of the climatic influence of Northern Hemisphere glaciation on already uplifted continents.

The clear indication of a decoupling of siliciclastic and chemical input to the ocean indicated by Figure 5 is an exciting and unexpected result of this compilation. Conventional wisdom indicates that physical weathering results in a large increase in grain surface area, which in turn allows more rapid chemical weathering. In fact, the Cenozoic record shows that a large increase in the rate of chemical weathering occurred 20 m.y. before any significant physical weathering. Furthermore, chemical weathering rates may have declined in the middle Miocene when rates of physical weathering, as recorded by the terrigenous input to oceans, increased markedly. A conclusion based on this information would indicate that chemical weathering is determined largely by hemispherical to global climate change and that physical weathering is controlled mostly by tectonism and uplift. The two effects combined in the Pliocene-Pleistocene to result in the increased chemical and particulate fluxes observed for that time (Fig. 5).

SUMMARY

On long time scales, the deposition of fine-grained muds in the deep sea appears to be controlled more by uplift in the sedimentary source region than by changing climate or sea level. Analysis of the sedimentary record shows that during the Cenozoic, siliciclastic deposition became important in middle to late Miocene time because of

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uplift in the Himalayas and North America (and probably elsewhere). Enhanced erosion in higher latitude regions associated with the onset of significant Northern Hemisphere glaciation further increased the amount of terrigenous material deposited in the ocean. When examined on intermediate time scales, the record of mineral accumulation provides information regarding the details of climatic changes on the continents and how the land environment may respond to orbital forcing. At any time scale, the existence of the terrestrial record in pelagic and hemipelagic sediments permits the only possible direct correlation of continental and oceanic histories of global change, a critically important aspect of paleoclimate research.

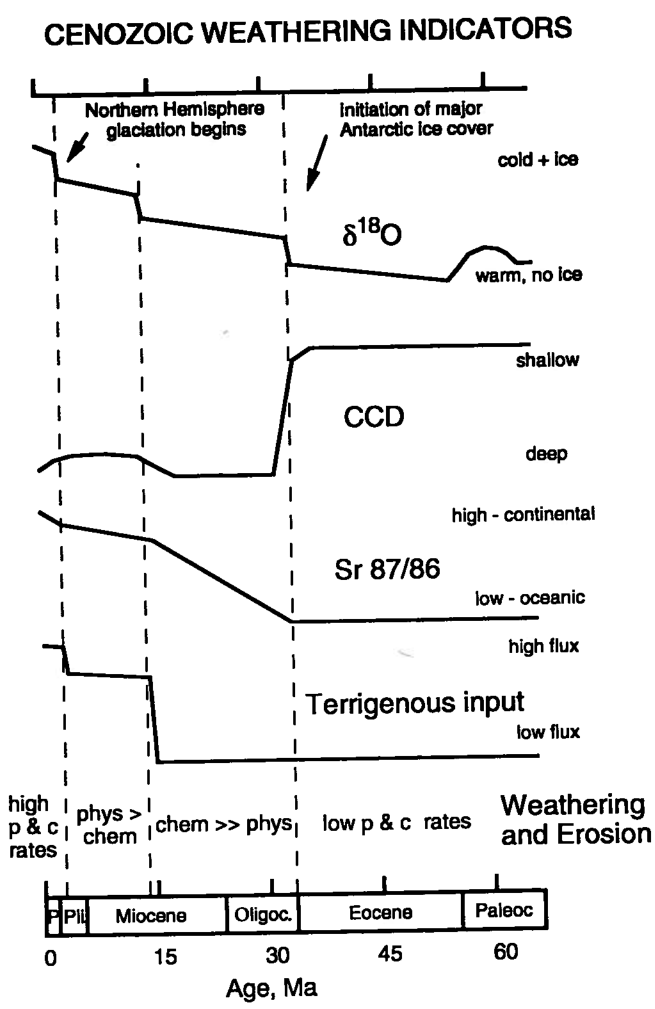

Figure 5. Chemical (c) and physical (p) indicators of Cenozoic weathering processes. Global climate is indicated by $\delta^{18}O$, chemical input to the ocean of Ca and radiogenic Sr^{87}/Sr^{86} is indicated by the CCD and Sr^{87}/Sr^{86} of seawater, particulate input to the ocean is indicated by terrigenous fluxes, and nature of weathering and erosion of continents: low rates in the Paleocene and Eocene, high chemical weathering rates in the Oligocene and early Miocene, high physical weathering and relatively reduced chemical weathering rates in the later Miocene and Pliocene, high physical and chemical weathering rates in the late Pliocene and Quaternary.

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REFERENCES CITED

Amano, K., and Taira, A., 1992, Two-phase uplift of Higher Himalayas since 17 Ma: Geology, v. 20, p. 391–394.

Barron, J., Larsen, B., and Baldauf, J. G., 1991, Evidence for late Eocene to early Oligocene Antarctic glaciation and observations on late Neogene glacial history of Antarctica: Results from Leg 119, *in* Barron, J., Larsen, G., et al., Proceedings of the Ocean Drilling Program, scientific results, Volume 119: College Station, Texas, Ocean Drilling Program, p. 869–891.

Brass, G. W., and Raman, C. V., 1990, Mineralogy of sediments from the Bengal Fan, *in* Cochran, J. R., Stowe, D. A. V., et al., Proceedings of the Ocean Drilling Program, scientific results, Volume 116: College Station, Texas, Ocean Drilling Program, p. 35–41.

Cande, S. C., and Kent, D. V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 97, p. 13,917–13,951.

Cochran, J. R., 1990, Himalayan uplift, sea level and the record of Bengal Fan sedimentation at the ODP Leg 116 sites, *in* Cochran, J. R., Stowe, D. A. V., et al., Proceedings of the Ocean Drilling Program, scientific results, Volume 116: College Station, Texas, Ocean Drilling Program, p. 397–414.

Duncan, R. A., Rea, D. K., Kidd, R. B., von Rad, U., and Weissel, J. K., editors, 1992, Synthesis of results from scientific drilling in the Indian Ocean: American Geophysical Union Monograph 70, 475 p.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1143–1167.

Heggie, D. C., Maris, A., Hudson, J., Dymond, J., Beach, R., and Cullen, J., 1987, Organic carbon oxidation and preservation in NW Atlantic continental margin sediments, *in* Weaver, P. P. E., and Thompson, J., eds., Geology and geochemistry of abyssal plains: Geological Society of London Special Publication 31, p. 215–236.

Hess, J., Bender, M. L., and Schilling, J.-G., 1986, Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to present: Science, v. 231, p. 979–984.

Honjo, S., Spencer, D. W., and Farrington, J. W., 1982, Deep advective transport of lithogenic particles in the Panama Basin: Science, v. 216, p. 516–518.

Hovan, S. A., and Rea, D. K., 1992, Paleocene/Eocene boundary changes in atmospheric and oceanic circulation: A Southern Hemisphere record: Geology, v. 20, p. 15–18.

Hovan, S. A., Rea, D. K., Pisias, N. G., and Shackleton, N. J., 1989, A direct link between the China loess and marine $\delta^{18}O$ records: Aeolian flux to the north Pacific: Nature, v. 340, p. 296–298.

Hovan, S. A., Rea, D. K., and Pisias, N. G., 1991, Late Pleistocene continental climate and oceanic variability recorded in northwest Pacific sediments: Paleoceanography, v. 6, p. 349–370.

Imbrie, J., and eight others, 1984, The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record, *in* Berger, A., et al., eds., Milankovitch and climate: Dordrecht, Netherlands, D. Reidel, p. 269–305.

Janecek, T. R., and Rea, D. K., 1983, Eolian deposition in the northeast Pacific Ocean: Cenozoic history of atmospheric circulation: Geological Society of America Bulletin, v. 94, p. 730–738.

Janecek, T. R., and Rea, D. K., 1985, Quaternary fluctuations in the northern hemisphere tradewinds and westerlies: Quaternary Research, v. 24, p. 150–163.

Johnson, N. M., Stix, J., Tauxe, L., Cerveny, P. F., and Tahirkheli, R. A. K., 1985, Paleomagnetic chronology, fluvial processes and tectonic implications of the Siwalik deposits near Chinji Village, Pakistan: Journal of Geology, v. 93, p. 27–40.

Kennett, J. P., and Stott, L. D., 1991, Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene: Nature, v. 353, p. 225–229.

Krissek, L. A., Morley, J. J., and Lofland, D. K., 1985, The occurrence, abundance and composition of ice-rafted debris in sediments from Deep Sea Drilling Project Sites 579 and 580, northwest Pacific, *in* Heath, G. R., Burckle, L. H., et al., Initial reports of the Deep Sea Drilling Project, Volume 86: Washington, D.C., U.S. Government Printing Office, p. 647–655.

Miller, K. G., Janecek, T. R., Katz, M., and Keil, D. J., 1987, Abyssal circulation and benthic foraminiferal changes near the Paleocene/Eocene boundary: Paleoceanography, v. 2, p. 741–761.

Molina-Cruz, A., 1977, The relation of the southern trade winds to upwelling processes during the last 75,000 years: Quaternary Research, v. 8, p. 324–338.

Pickering, K. T., Hiscott, R. N., and Hein, F. J., 1989, Deep marine environments clastic sedimentation and tectonics: London, Unwin Hyman, 416 p.

Poag, C. W., 1992, U.S. Middle Atlantic continental rise: Provenance dispersal and deposition of Jurassic to Quaternary sediments, *in* Poag, C. W., and de Graciansky, P. C., eds., Geologic evolution of Atlantic continental rises: New York, Van Nostrand Reinhold, p. 100–156.

Poag, C. W., and de Graciansky, P. C., editors, 1992, Geologic evolution of Atlantic continental rises: New York, Van Nostrand Reinhold, 378 p.

Prell, W. L., Murray, D. W., Clemens, S. C., and Anderson, D. M., 1992, Evolution and variability of the Indian Ocean summer monsoon: Evidence from the western Arabian Sea drilling program, *in* Duncan, R. A., et al., eds., Synthesis of results from scientific drilling in the Indian Ocean: American Geophysical Union Monograph 70, p. 447–469.

Prospero, J. M., 1981, Eolian transport to the world ocean, *in* Emiliani, C. ed., The sea, Volume 7, The oceanic lithosphere: New York, John Wiley & Sons, p. 801–874.

Prospero, J. M., Charlson, R. J., Monhnen, V., Jaenicke, R., Delany, A. C., Moyers, J., Zoller, W., and Rahn, K., 1983, The atmospheric aerosol system: An overview: Reviews of Geophysics and Space Physics, v. 21, p. 1607–1629.

Rea, D. K., 1992, Delivery of Himalayan sediment to the northern Indian Ocean and its relation to global climate, sea level, uplift, and seawater strontium, *in* Duncan, R. A., et al., eds., Synthesis of results from scientific drilling in the Indian Ocean: American Geophysical Union Monograph 70, p. 387–402.

Rea, D. K., and Schrader, H., 1985, Late Pliocene onset of glaciation: Ice rafting and diatom stratigraphy of North Pacific DSDP cores: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 49, p. 313–325.

Rea, D. K., Leinen, M., and Janecek, T. R., 1985, Geologic approach to the long-term history of atmospheric circulation: Science, v. 227, p. 721–725.

Rea, D. K., Zachos, J. C., Owen, R. M., and Gingerich, P. D., 1990, Global change at the Paleocene-Eocene boundary: Climatic and evolutionary consequences of tectonic events: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 79, p. 117–128.

Ruddiman, W.F., 1977, Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat 40° to 65°N): Geological Society of America Bulletin, v. 88, p. 1813–1827.

Shackleton, N. J., and 16 others, 1984a, Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region: Nature, v. 307, p. 620–623.

Shackleton, N. J., and Members of the Shipboard Scientific Party, 1984b, Accumulation rates in Leg 74 sediments, *in* Moore, T. C., Jr., Rabinowitz, P. D., et al., Initial reports of the Deep Sea Drilling Project, Volume 74: Washington, D.C., U.S. Government Printing Office, p. 621–644.

Saito, C., Noriki, S., and Tsunogai, S., 1992, Particulate flux of Al, a component of land origin, in the western North Pacific: Deep-Sea Research, v. 39, p. 1315–1327.

Sloan, L. C., Walker, J. C. G., Moore, T. C., Jr., Rea, D. K., and Zachos, J. C., 1992, Possible methane-induced polar warming in the early Eocene: Nature, v. 357, p. 320–322.

van Andel, T. H., 1975, Mesozoic/Cenozoic calcite compensation depth and the global distribution of calcareous sediments: Earth and Planetary Science Letters, v. 26, p. 187–194.

Van der Hammen, T., 1985, The Plio-Pleistocene climatic record of the tropical Andes: Geological Society of London Journal, v. 142, p. 483–489.

Windom, H. L., 1975, Eolian contributions to marine sediments: Journal of Sedimentary Petrology, v. 45, p. 520–529.

Yokoyama, K., Amano, K., Taira, A., and Saito, Y., 1990, Mineralogy of silts from the Bengal Fan, *in* Cochran, J. R., Stowe, D. A. V., et al., Proceedings of the Ocean Drilling Program, scientific results, Volume 116: College Station, Texas, Ocean Drilling Program, p. 59–73.

Zachos, J. C., Breza, J., and Wise, S. W., Jr., 1992, Early Oligocene ice-sheet expansion on Antarctica: Sedimentological and isotopic evidence from Kerguelen Plateau: Geology, v. 20, p. 569–573.

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