RESEARCH ARTICLE

Geologic Approach to the Long-Term History of Atmospheric Circulation

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During the past decade and a half, three categories of data have been utilized by paleoclimatologists to address broad-scale questions about the history of climate. The types of data include (i) sediment microfaunal and microfloral assemblages, which are commonly related to climate parameters through multivariate statistical or empirical mathematical analyses (*1, 2*); (ii) the accumulation rate of the biogenic components of pelagic sediment, such as calcium carbonate and opal (*3–5*); and (iii) the oxygen and carbon isotopic composition of planktonic and benthic foraminifera (*6–8*). Reasonable inferences for past sea-surface temperature and salinity, the location of oceanographic frontal zones, sea-surface biological productivity, deep-ocean carbonate dissolution, the volume of continental ice cover, and the fractionation of carbon between the deep and shallow waters can be drawn from these data sets. Much effort has been concentrated on understanding the Pliocene-Pleistocene ice ages (0 to 2.5 million years ago), but these techniques also have been applied to the Cretaceous (65 to 144 million years ago) and all Cenozoic (0 to 65 million years ago) epochs.

Because atmospheric circulation parameters are primary climate variables, a common interpretative step after the information on preexisting climatic conditions has been assembled is to develop qualitative models (for example, more opal = more productivity = more upwelling = stronger winds) or quantitative models (for example, global circulation models based on sea-surface temperature data) to infer past atmospheric circulation. Verification of the relation implied by such models is important not only to test their validity but also because such models provide input to the prediction of climate change on continents. For example, the predicted CO_2-induced warming from deforestation and the burning of fossil fuels may cause a number of changes, such as alterations in the length of the growing season and in rainfall patterns, that are now being studied with the aid of atmospheric circulation models.

We present here a fourth category of paleoclimate indicators that provide direct information about both the intensity of atmospheric circulation and the availability of material for eolian transport from the continents: the record provided by eolian dust accumulating in pelagic sediments.

Abstract. *Eolian dust preserved in deep-sea pelagic sediments can be used as a proxy indicator of paleoclimate. Analyses of the particle size, composition, and mass accumulation rate of dust grains provide independent evidence of the intensity of atmospheric circulation and the availability of material in the eolian source region. These data provide information on atmospheric circulation and on the climate of the source area at time scales ranging from 10^3 to 10^8 years and have the potential to test computer-generated global circulation models.*

Eolian deposition in the deep sea. Eolian contributions to deep-sea sediments have been a topic of research for nearly 25 years (*9*). Windom (*10*) suggested that up to 75 percent of the nonbiogenic component of North Pacific deep-sea sediment was atmospheric dust fallout, an estimate strengthened by Ferguson *et al.* (*11*), who first demonstrated the similarity between the mineralogy of eolian dust and that of deep North Pacific sediments. Wind-borne dusts have been sampled from ships and land-based stations (*12–17*), and the mineralogy of dust has been compared to that of surface sediments (*14, 18–20*). The results of the various sampling programs indicate that atmospherically transported dust is a significant component of pelagic sediments (*11, 14, 21*).

Away from the mouths of major rivers, the patterns of sediment mineralogy (*19, 22*) parallel the zonal wind regimes. The zonal pattern of sediment mineralogy is apparent even beneath the north-south–flowing surface currents at the boundaries of the subtropical gyres. Incorporation of small grains into fecal pellets by feeding zooplankton and the rapid settling of these pellets and of large amorphous aggregates at a rate of hundreds of meters per day (*23*) quickly removes eolian dust (*24*) and all other particles (*25*) from the effects of ocean-surface circulation. Thus, ocean-floor sedimentary assemblages mimic sea-surface assemblages of input components, and surface current–related smearing of sedimentary patterns is minimal (*26*).

Eolian grains now in deep-sea sediments originate largely from arid and semiarid regions of the continents. Winds blowing across the land surface pick up and carry dust grains as large as hundreds of micrometers in diameter (*27*). Initially the size distribution of this material will reflect that of the parent soil, but larger grains begin to settle out immediately, and, after transport for some time and distance, wind-borne dusts are characterized by grains 1 to 10 μm in diameter (*19, 27–29*). When the settling velocity of small eolian grains is some fraction of the vertical velocity fluctuation inherent to the turbulence of the atmosphere, these grains, a minor portion of the initial dust load, remain in suspension indefinitely (*29, 30*). These grains are carried for global distances in the upper troposphere and generally are removed by rainout (*31*). Both air- and land-based sampling (*15, 16, 20, 32*) and theoretical calculations (*19, 29*) show that beyond a distance of 1000 to 2000 km from the source the size distribution of the grains changes very little. At any distal location, therefore, changes in the size of these equilibrium grains should somehow represent changes in the intensity of the zonal winds (*33*).

The best long-term record of present-day eolian transport, that accumulated by Prospero and his co-workers, relates the flux of dust crossing the North Atlantic to climatic conditions in the Saharan-Sahelian source region. Monthly values show increased dust transport during the spring and early summer with an order of

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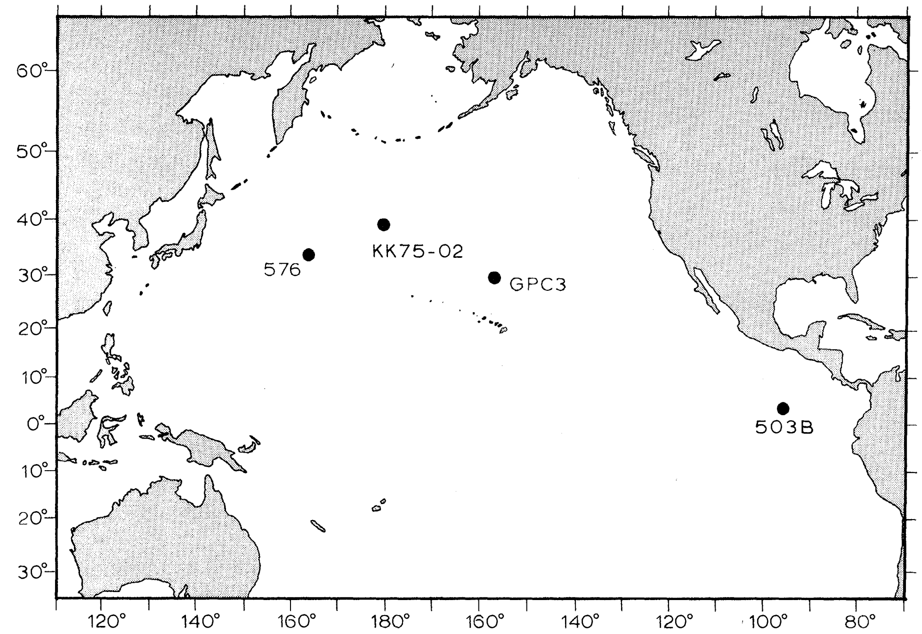

Fig. 1. Index map of the Pacific Ocean showing the locations of cores discussed in the text.

magnitude variation in any given year (*34, 35*). The annual cycles correlate with the climatology of arid North Africa but not with the general intensity of Northern Hemisphere trade winds, which are stronger in the winter (*36*). On a longer term basis, the flux of dust across the Atlantic showed a threefold increase during the height of the Sahelian drought, 1973 and 1974, in comparison to more normal years before and since (*34, 37*). These data and a similar data set on dust collected in Hawaii (*38*) provide evidence that the amount of dust transported depends on the availability of material, in this case determined by the degree of aridity of the source region. Humid, vegetated regions provide less mineral aerosol than arid areas, a common working assumption held by most investigators of past atmospheric transport (*39–42*).

The grain size and concentration of eolian quartz in ocean floor surface sediments have been determined by Dauphin (*43*) for 122 locations in the North and Southeast Pacific and North Atlantic oceans. His work shows that quartz grain size decreases rapidly over the first 1500 km from shore and thereafter decreases gradually for many thousands of kilometers. More specifically, along a 5000-km west-to-east transect across the North Pacific, the grain size of eolian quartz decreases from 10.3 μm (6.6 ϕ) (*44*) to 7.4 μm (7.1 ϕ) (*43*).

Quartz and other minerals occurring as relatively large grains make up only 10 to 30 percent of the total eolian load; essentially all the rest is much finer grained material and is dominated by clay minerals. Our work with the total eolian component has shown a very small reduction in the average grain size along nearly the same transect as that reported by Dauphin, from 2.8 μm (8.5 ϕ) to 2.4 μm (8.7 ϕ) in a distance of about 3600 km (*45*). These small grains appear to be essentially in equilibrium with the intensity of the transporting zonal winds.

Analytical methods, accuracy, and applicability. A primary factor controlling our ability to make inferences about past atmospheric transport is the selection of appropriate samples. These must be from sites that are not contaminated by fine-grained minerals transported by other processes. The most significant other processes that bring minerals to the sea floor include hemipelagic sedimentation near continents, turbidite sedimentation, and, in high latitudes, ice rafting.

We have determined the three significant parameters of eolian deposition: the mass flux of dust to the sea floor, the composition of the dust, and the grain size of the eolian grains. Dust grains are isolated from freeze-dried sediment samples by a series of extractions that remove noneolian components, and the weight percentage of the dust is then determined (*46*). The mass accumulation rate (MAR) of the eolian component is a flux value and a true measure of eolian input to the ocean, which concentration data are not. The MAR is the product of the percentage by weight of eolian dust and the total sediment MAR; this latter (in grams per square centimeter per 1000 years) is a product of the linear sedimentation rate (LSR) (in centimeters per 1000 years) determined from the biostratigraphy or magnetostratigraphy and the dry bulk density of the sample (in grams per cubic centimeter) (*46*). The precision of our extraction procedure is ±5 percent of the percentage by weight. The accuracy of the eolian MAR values depends more on errors resulting from nonlinearity of the sedimentation rate than on the extraction procedure. The mineral composition of the eolian sediment can be determined by quantitative x-ray diffraction techniques (*47*). Analyses for quartz content are accurate to $\pm < 1$ percent (*48*), whereas those for clay mineral content are accurate to ±5 percent (*22*). In the grain size analyses we used a particle size analyzer that gives the distribution of grains, by volume, in the diameter range of 16 μm (6 ϕ) to 1 μm (10 ϕ). The accuracy of these measurements is ±0.03 to 0.05 ϕ (*44*) for the data reported below.

The MAR data are indicative of the availability of material in the source area, which in turn is related to climate. Mineralogy may record some aspects of source-area climate but is more helpful in distinguishing between eolian source regions (*20, 22, 48*). The size of the eolian grains recovered can provide a record of the intensity of the transporting winds (*33, 39, 42, 43, 49*). In those cases where detailed data sets have been compiled (*42, 45, 50*), the eolian MAR and grain size vary independently. These parameters apparently respond to different aspects of past climates and are analogous in concept to the capacity and competence of rivers.

Our work to date has been in the North Pacific, which is sedimentologically far more simple than the Atlantic Ocean. The North Pacific westerlies have a major dust source in Asia, and the trade winds a smaller source in Central and northern South America. Where we have been able to make independent tests, our dust flux values calculated from ocean floor surface sediments are in good agreement with present-day measured values. At Enewetak (11°N, 162°E) the present-day range of deposition rates has been estimated to be from 15 (*51*) to 38 mg cm^{-2} (10^3 $year)^{-1}$ (*52*). Our closest sample site to Enewetak is Deep Sea Drilling Project (DSDP) site 463 (21°N, 174°E), where the average dust MAR during Brunhes time (0 to 0.7 million years ago) is 28 mg cm^{-2} (10^3 $year)^{-1}$ (*49*). In a core raised from an area near 9°N, 104°W, the eolian flux from the surficial sediment sample was 129 mg cm^{-2} (10^3 $year)^{-1}$ (*53*). Sediment-trap data from the same location give a value for mineral flux to the sea floor of

110 to 126 mg cm^{-2} (10^3 year)$^{-1}$ (*54*). Eolian sediments accumulating in the northwestern Pacific at rates of 200 to 1800 mg cm^{-2} (10^3 year)$^{-1}$ (*45, 49, 50*) are consistent with an extrapolation between the dust fluxes measured in Japan and Hawaii (*14*). Comparisons such as these give us confidence that we can make reliable measurements of the eolian dust flux to the deep sea (*46*).

There is one additional characteristic of our sediment samples that is important to an understanding of the data record. Samples arriving in the laboratory span 1 to 2 cm of a core. Linear sedimentation rates for the cores discussed below range from a low of about 0.02 cm (10^3 year)$^{-1}$ in the most slowly accumulating intervals of core LL44-GPC3 to a maximum of about 1.4 cm (10^3 year)$^{-1}$ in core KK75-02, so a 2-cm sample can represent 1400 to 100,000 years. Benthic fauna continuously rework ocean-floor sediments after their deposition and further smear temporally fluctuating sedimentary signals. Each value we measure, then, is an integrated representation of at least 2000 years of eolian processes. Sediments thus record a long-term climatic signal probably not much influenced by the vagaries of synoptic meteorology, the exact transport paths of individual grains, or interannual changes in the number of dust storms. Long-term changes on time scales of 1000 years or more in any of these phenomena may be recorded, but these then would fall in the realm of climatic shifts.

Dust accumulation beneath the westerlies in the North Pacific gives a broad picture of the total upwind source area, presumably much of subtropical to subpolar Asia. It is unlikely that the relative importance of any local or subregional source area could be determined from the type of data presented here. Major latitudinal shifts in dust sources should be decipherable, although it has been shown elsewhere that the maximum eolian MAR values in the North Pacific have remained centered along 38° to 40°N for the past 30,000 years, spanning the time from before the last glacial maximum to the present (*55*).

Cenozoic record of eolian deposition. Two studies illustrate the types of information that can be derived from the eolian component of pelagic sediments. The first is a 70-million-year record of eolian input to the North Pacific. We have detailed information from two apparently continuous cores that span the entire Cenozoic: core LL44-GPC3, a pelagic clay core raised from 30.3°N, 157.8°W (*22, 56*), and sediments from DSDP Site 576 (32.4°N, 164.3°E), composed of siliceous clays grading down to pelagic clays (*45, 48*). These cores are separated by 3600 km (Fig. 1).

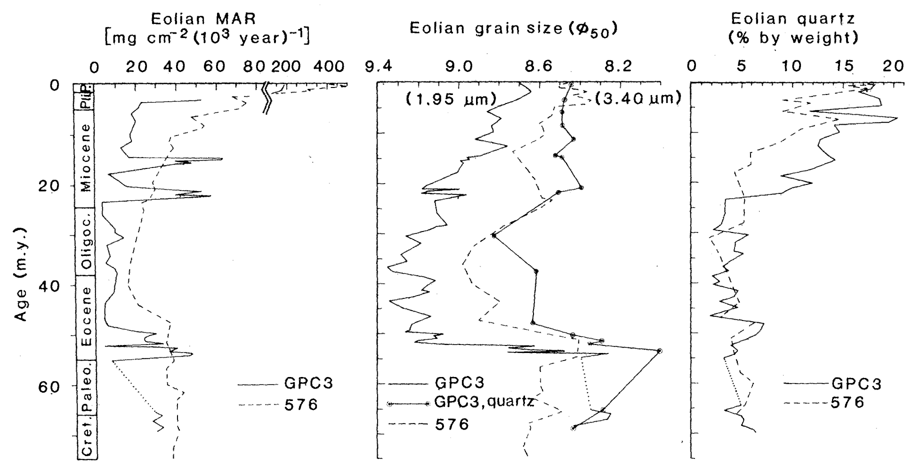

Fig. 2. Mass accumulation rate (MAR), grain size (ϕ_{50}) of both the total eolian component and of quartz grains extracted from core GPC3 by J. P. Dauphin, and percentage of quartz in eolian sediments from the North Pacific Ocean. The MAR and size data for core GPC3 are from Janecek and Rea (*56*) with revised stratigraphy from Leinen (*48*) and Leinen and Heath (*70*), and for Hole 576 from Janecek (*45*). All quartz data are from Leinen (*48*); m.y., million years.

The temporal pattern of mineralogy, mass flux, and grain size of both the total eolian load and the extracted quartz samples from core GPC3 and Site 576 are in good agreement (Fig. 2), illustrating the broad-scale uniformity of eolian processes over the past 70 million years. Core GPC3 was more closely sampled than Site 576, and so the GPC3 curves show considerably more detail. The major features of both MAR curves are similar: very high MAR values during the past 2 or 3 million years, then a gradual decrease to the low values characteristic of Oligocene and Eocene time, followed by an increase to the moderate values of early Eocene and older sediments. Two sharp peaks at 15 to 16 million years ago and 21 to 23 million years ago are superimposed on this pattern in core GPC3. Site 576, lying closer to Asia, exhibits a higher eolian MAR and slightly coarser grain diameter (*45*). The percentage of quartz in the mineral component of each core is similar, about 5 percent in materials older than 20 million years and 10 to 15 percent in younger sediments, although during the interval between 10 and 20 million years the quartz records do not match well (*48*).

These data show that large-scale changes in the atmospheric circulation factors controlling dust transport have occurred during the past 70 million years. An important and unexpected result of this work was documentation of a sudden decrease in the grain size of eolian sediments in both cores that occurred during the early Eocene (Fig. 2). This is most reasonably interpreted as a decrease in the intensity of atmospheric circulation. Atmospheric circulation remained less intense until 35 to 40 million years ago, when wind intensity began a long-term overall increase culminating in the maximum associated with the Pliocene-Pleistocene glaciations (*56*). The post-Eocene data support the idea of Cenozoic polar cooling and evolution of the cryosphere beginning about 38 million years ago in the Antarctic (*57*). The similarity of the two grain-size curves for the Paleocene and latest Cretaceous (Fig. 2) strongly implies that atmospheric circulation at that time was as vigorous as that of the past few million years. This conclusion is contrary to the general impression of the Cretaceous as a time of warm and equitable climates, characterized by sluggish ocean circulation (*58*). It supports, however, the results of computer-generated circulation models for Cretaceous conditions that indicate an atmospheric circulation intensity similar to that of the present (*59*). To our knowledge, this is the first realistic test of computer models of atmospheric circulation.

Eolian MAR values were lowest during the middle Tertiary, a time of relatively humid continental climates. Dust transport began to increase during the early Miocene, and during the Pliocene it increased by up to an order of magnitude with the onset of Northern Hemisphere glaciation (*45, 56*). These data emphasize the general correlation between glacial ages and factors conducive to dust availability such as global aridity (*41, 60*), removal of vegetation, and exposure of soils from lake beds and continental margins to wind erosion.

Quaternary record of climatic fluctua-

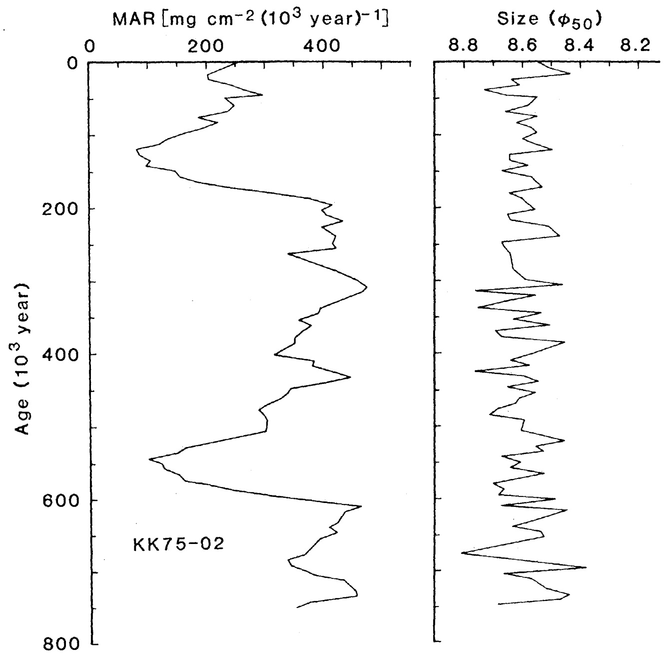

Fig. 3. Mass accumulation rate and grain size of eolian sediments in core KK75-02 from the central North Pacific Ocean. Data are from Janecek (*61*).

tion. The second data set we wish to discuss bears on the nature of atmospheric circulation and dust flux during the past several glacial and interglacial cycles. Piston core KK75-02, raised from 5465 m at 38.6°N, 279.3°E (Fig. 1), contains siliceous clay and clayey siliceous ooze. Stratigraphic control is based on four datable biostratigraphic horizons (*61*) and the Brunhes-Matuyama magnetic reversal boundary at 975 cm (*62*). The core was sampled at 10-cm intervals, providing a sample about every 7000 years. Data from these samples (Fig. 3) provide a detailed record of the Northern Hemisphere westerlies and of Asian climate that spans the last 750×10^3 years.

Eolian MAR values average about 400 mg cm^{-2} $(10^3 \text{ year})^{-1}$ and show relative maxima approximately every 110×10^3 years (Fig. 3), with two pronounced minima at 120×10^3 and 540×10^3 years. In general, times of accumulation maxima correspond to interglacial periods (*50*). The similarity of the eolian MAR pattern to the 105×10^3 year ice-volume signal (*50*) is not surprising as the advance and retreat of continental ice would dominate the source area climate in mid- to high latitudes.

A similar pattern of eolian MAR values occurs at DSDP Hole 503B in the eastern equatorial Pacific (Fig. 1). Eolian flux data for the past 400×10^3 years at this site also indicate more dust transport during interglacials and less during glacial periods from the Central and northern South American source regions (*42*). These results, which imply arid interglacial and humid glacial times, contrast with some computer models of ice-age climate (*63*) and the observation that the Sahara may have supplied more eolian material to the eastern Atlantic during glacial times (*41, 43*) but are in agreement with palynological data from the Colombian Andes suggesting higher lake levels during glacial periods (*64*).

The grain size of eolian dust in core KK75-02 ranges from a diameter of 2.23 μm (8.81 φ) to 3.02 μm (8.37 φ) (Fig. 3). High-frequency fluctuations characterize the grain-size record and indicate an average change in wind intensity of 22 percent (*65*), in general agreement with the fluctuations in wind intensity predicted by circulation models (*66*). The amplitude of the inferred wind fluctuations changed markedly about 250×10^3 years ago from 27 percent before that time to 17 percent more recently (*50, 61*). A similar reduction in the amplitude of trade wind fluctuations, from 47 to 26 percent occurs at the same time at Hole 503B (*42, 50*). Other paleoclimatic indicators have also suggested changes in oceanic or atmospheric circulation about 250×10^3 years ago (*4, 67*).

Spectral analysis of the eolian grain-size data for core KK75-02 reveals three significant peaks in variance corresponding to periods of 104×10^3, 41×10^3, and 23×10^3 years (*50, 61*). These periods correspond to the periods calculated by Milankovitch for the earth's orbital eccentricity, obliquity, and precession and provide the first documentation that atmospheric circulation, like other paleoclimatic proxy indicators (*68*), responds to orbitally forced stimuli.

Summary: Information and ignorance. Our data and those of other investigators (*41, 43, 69*) demonstrate that a sedimentary record exists that can be used to construct a quantitative, geologic history of parameters related to atmospheric circulation. The record of the zonal winds is uniform over long distances and times (Figs. 1 and 2), and so data from one well-chosen core can characterize a broad area of a zonal wind belt. Our data have revealed surprisingly vigorous atmospheric circulation during the Late Cretaceous and Paleocene, a sudden reduction in the early Eocene, and stepwise increases during the later Cenozoic (Fig. 2) (*22, 45, 48, 56*). Over geologic times dust input to the North Pacific reflects the change from early and mid-Cenozoic continental humidity to the aridity and increased dust availability of the late Cenozoic.

Detailed records of Quaternary fluctuations show that, in the North Pacific, the flux of dust to the deep sea appears to vary inversely with ice volume, with interglacial times having higher MAR values and thus being more arid than glacial periods. The eolian grain-size record shows that the intensity of atmospheric circulation varies much more rapidly than the 105×10^3 year ice-volume record and responds to the orbital cycles.

Our approach to deciphering the geologic history of wind can be applied to several problems in paleoclimatology, but various uncertainties exist. One of these is the relation between synoptic meteorology on yearly or decadal time scales to climatology at time scales of millennia. Do transport episodes and pathways remain effectively constant when averaged over thousands of years? Are the coarser quartz particles transported only by the more energetic or turbulent portions of dust storms, and, if so, what additional or different information does quartz granulometry provide over measurements of the total dust input? Is there a better way to relate the essentially equilibrium grain size of dust to wind "intensity" that can give credible paleovelocity values, or must this be done empirically? These and other far-ranging questions will require for their solution the cooperative efforts of atmospheric and oceanic scientists engaged in the study of paleoclimatology.

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