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Late Miocene Origin of the Benguela Upswelling System off Northern Namibia

Abstract. *Deep Sea Drilling Project cores collected at site 362/362A suggest the time of initiation of the Benguela upwelling system off northern Namibia. Studies of sediment accumulation rates, diatom abundances, microfossil temperature preferences (for planktic foraminifers, calcareous nannoplankton, and silicoflagellates), productivity (expressed as the organic carbon content), and phosphorus incorporation in calcareous skeletons all suggest that major, sustained upwelling began in the early late Miocene. Upwelling brought cold, nutrient-rich waters to the surface, and the modern Benguela system dates from this time (about 10 million years before the present).*

The Benguela upwelling system ("Benguela Current") is the northward-flowing, cold, upwelled water found within 100 nautical miles (1 nautical mile = 1852 m) of the west coast of South Africa and Namibia (South West Africa) between 15°S and 34°S (*1*) (Fig. 1). These cold, upwelled waters are extremely rich in phosphate, nitrate, and silicate—nutrients which support a vast population of phytoplankton. The abundance of phytoplankton, in turn, provides the basic food stock that makes this one of the world's richest fishing grounds. The purpose of this report is to suggest a time for the origin of the Benguela system.

Late Cretaceous (*2*), Eocene (*3*), or early Oligocene (*4*) have all been suggested or implied as possible times for the establishment of the Benguela system. Recent work on Deep Sea Drilling Project (DSDP) cores (site 362/362A) collected from the continental margin off northern Namibia indicates that strong, persistent upwelling of cold waters (that is, the present Benguela system) began in the early late Miocene. Evidence from sedimentological, micropaleontological, and geochemical studies supports this conclusion.

Site 362/362A (Fig. 1) is today under the influence of the Benguela system (*5*) and has been throughout all later Cenozoic time (*6*). Fossil skeletons of planktic organisms that once lived in the waters of the Benguela system now reside in sea-floor sediment; these sediments, and the fossils of which they are largely composed, record the history of changing conditions in the overlying water masses.

The onset or intensification of upwelling would bring more nutrients to the surface, thus promoting prolific plankton growth and ultimately an increase in plankton skeletons deposited as sediment on the sea floor. A major increase in pelagic-biogenic sediment accumulation may therefore reflect upwelling. Sediment accumulation rates for site 362/362A (Fig. 2) have been corrected for postburial compaction on the basis of measured downhole variations in porosity and gravimetric bulk density (*7*). Two major peaks of rapid sediment accumulation are apparent in Fig. 2: one in the mid-Oligocene and one in the late Miocene.

The very rapid accumulation in mid-Oligocene times reflects the enormous blooms of a single nannoplankter, *Braarudosphaera*. An interval more than 50 m thick is overwhelmingly composed of fragments of this single genus [up to 95 percent in some beds (*7*)]. The *Braarudosphaera* bloom was not a local event occurring solely off northern Namibia. This distinctive chalk also appears during the same time interval in the central and western South Atlantic [on the Mid-Atlantic Ridge and in the Brazil and Argentine basins (*7*)]. The enormous *Braarudosphaera* blooms at this time were probably a response to a regional South Atlantic oceanographic event. The nature and causes of this event are still speculative (*8*). However, we can be cer-

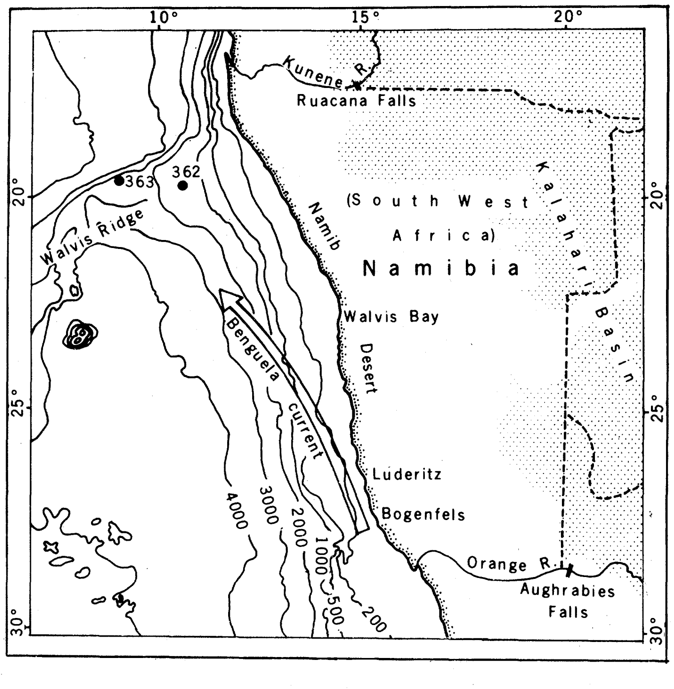

Fig. 1. Location map showing site 362/362A. Isobaths are in meters. The water depth at the site is 1325 m; the subsea-floor drilling depth was 1081 m.

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tain that the rapid accumulation rate during the mid-Oligocene at site 362/362A is related to this regional event and not to local Benguela upwelling.

The accumulation rate increases sharply again in the late Miocene, rising to almost 1600 g/cm^2 per 10^6 years (Fig. 2). Increasing numbers of each of several planktic groups (foraminifers, calcareous nannoplankton, diatoms, radiolarians, and silicoflagellates) account for the increased sediment accumulation rates after the early late Miocene (*6, 7*).

I have no ready explanation for the drop in the accumulation rate near the Miocene-Pliocene boundary; it may be more than just coincidental, however, that there was a strong but brief Antarctic glaciation at this precise time (during the Kapitean Stage, which spans the Miocene-Pliocene boundary in New Zealand). It has been suggested that this glacial event lowered sea level sharply, perhaps even isolating the Mediterranean from the open ocean and inducing the Messinian salinity crisis (*9*). If so, this sea-level lowering might have shifted the upwelling belt far enough offshore to reduce substantially the accumulation rate at site 362/362A. Additional and independent support for a regression close to the Miocene-Pliocene boundary has been presented by Siesser and Dingle (*10*).

The amount, grain size, and surface texture of presumably windblown quartz grains were examined to test the assumed correlation between upwelling and increased wind velocity. The results were inconclusive, possibly because of the small amount of terrigenous quartz in the samples.

Paleontological evidence comes from several planktic groups. A great abundance of diatoms in mid-latitude, open-ocean waters is strong evidence for upwelling (*11*), since upwelled waters are rich in the nutrients on which diatoms depend. Diatom frustules are absent from middle Eocene to earliest late Miocene times in the cores collected at site 362/362A (*6*). They begin to occur only in the early late Miocene, increasing markedly from about the end of the late Miocene and continuing their overall increase into the Pleistocene (*6*) where their skeletons comprise up to 90 percent of some late Pleistocene cores (*7*). Abundant diatoms are an important recognition criterion for sediments influenced by upwelling (*11*), and their absence in the older sediments suggests that no upwelling occurred over site 362/362A before early late Miocene times.

Some species of microplankton are closely restricted to water masses with narrowly defined temperature ranges. Changing ratios of cold- and warm-water planktic foraminifers, calcareous nannoplankton, and silicoflagellates indicate a marked change in water temperatures over this site during the Tertiary. Planktic foraminifers are dominated by tropical species from middle Eocene to early/middle Miocene times (*12, 13*). Tropical species become scarce or absent from the late Miocene onward (*13*), whereas cool-water species, such as *Globigerina bulloides* and *G. quinqueloba*, become prominent. The dominance of the cool-water form *Globorotalia miozea* among the keeled globorotalids also suggests cooling waters (*13*).

Nannoplankton show a similar trend (*14*). Warm waters in Eocene times are indicated by the low ratio of *Chiasmolithus* to *Discoaster* and in the Oligocene to mid-Miocene interval by the frequent occurrence of warm-water forms such as *Sphenolithus* and *Discoaster*. From middle or late Miocene times onward, marked cooling is indicated. Discoasters become scarce in the late Miocene to Pliocene, and the cool-water form *Coccolithus pelagicus* becomes abundant in the Pleistocene. The great relative abundance (26 to 64 percent) of *Distephanus* among the silicoflagellates during the Pliocene also indicates cool waters at this time (*8*). I believe this marked temperature drop in late Miocene times reflects the major introduction of cold waters and thus the establishment of the modern Benguela system.

Geochemical evidence supports this conclusion. High productivity in the Benguela system is the result of upwelling, nutrient-rich waters; this productivity (primary plus secondary) can be measured in terms of organic carbon (Fig. 3). Organic carbon values are low from the middle Eocene to the middle Miocene (less than 0.5 percent) (*6, 15*), which is normal for most pelagic oceanic sediments. However, a sustained rise in the organic carbon content begins in early late Miocene times, culminating in very high values (5.3 and 4.8 percent) in the Pleistocene (*15*). This result strongly suggests the initiation of upwelling in the early late Miocene, with progressive intensification of upwelling in Pliocene and Pleistocene times.

It is well known that plankton extract

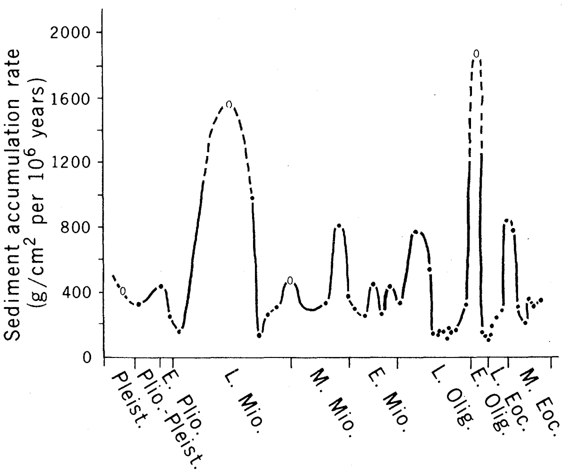

Fig. 2. Total sediment accumulation rates for DSDP site 362/362A, redrawn from Bolli *et al.* (*7*). Rates have been corrected for postburial compaction (*7*). Open circles are projected from calculations of the $CaCO_3$ accumulation rate.

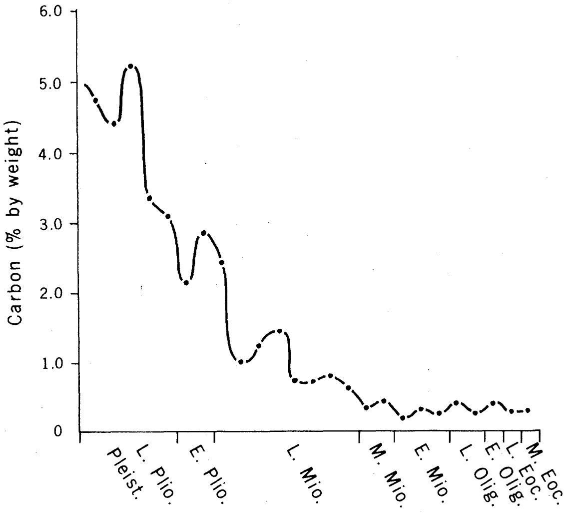

Fig. 3. Organic carbon content in cores from DSDP site 362/362A. The curve is plotted from tabular data presented by Erdman and Schorno (*15*).

minor and trace elements from seawater and incorporate these elements in their skeletons. Electron microprobe analyses of phosphorus in the calcite skeletons of calcareous nannoplankton show that, after a middle Eocene high, these plants incorporated low, but fluctuating amounts of phosphorus from early Oligocene to middle Miocene times (*16*). A slight, but steadily increasing phosphorus uptake occurs from late Miocene times onward (*16*). I believe that this increase reflects greater availability of phosphorus in the water from late Miocene times, since phosphorus is one of the major nutrients supplied by upwelled waters.

Sedimentological, paleontological, and geochemical evidence indicate that the Benguela upwelling system off northern Namibia originated in the early late Miocene (about 10 million years before the present). The evidence presented actually establishes the times of initiation of upwelling above site 362/362A only. Whether upwelling began all along the western coast of southern Africa at the same time is a moot point. Intuitively, it seems that, once the atmospheric and other conditions that drive the Benguela upwelling were in effect, upwelling would begin all along the coast with only a slight delay from place to place.

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Sediment-Water Chemical Exchange in the Coastal Zone Traced by in situ Radon-222 Flux Measurements

Abstract. *In situ radon-222 flux experiments conducted in benthic chambers in Cape Lookout Bight, a small marine basin on the North Carolina coast, reveal that enhanced chemical transport across the sediment-water interface during summer months is caused by abiogenic bubble tube structures. Transport rates for dissolved radon, methane, and ammonium more than three times greater than those predicted on the basis of molecular diffusion occur when open tubes are maintained by semidiurnal low-tide bubbling.*

Chemical exchange across the sediment-water interface is an important process regulating the composition of the oceans (*1*). In the coastal zone, organic-rich sediments can supply a major fraction of the nutrient requirements of primary producers in overlying water (*2*). The sediments are the site of intense remineralization during which microbial heterotrophs convert deposited organic carbon, nitrogen, and other elements into dissolved NH_4^+, HCO_3^-, CH_4, and other chemical species (*3*). The remineralization reactions together with diffusive transport, adsorption, and other processes produce concentrations of these products in the interstitial waters of the sediments which generally increase with depth. The rates of transport of the dissolved species from the sediments to the water column are, in turn, controlled by both the magnitude of the resulting concentration gradients in the interstitial water and the mechanism of sediment-water exchange.

Transport by molecular diffusion can be predicted by Fick's first law, modified for application to sediments (*4*):

$$J = -\phi D_s (\partial C/\partial z)_{z=0} \tag{1}$$

where J is the vertical diffusive flux across the sediment-water interface, ϕ is the sediment porosity, D_s is the whole (bulk) sediment diffusion coefficient (*4*), and $(\partial C/\partial z)_{z=0}$ is the vertical concentration gradient in the interstitial water at the interface.

One calculates fluxes across the sediment-water interface in the ocean by means of Eq. 1, using measured porosities and concentration gradients coupled with estimated molecular diffusion coefficients, since molecular diffusion coefficients are difficult to measure experimentally. However, if the flux as well as the porosity and concentration gradient

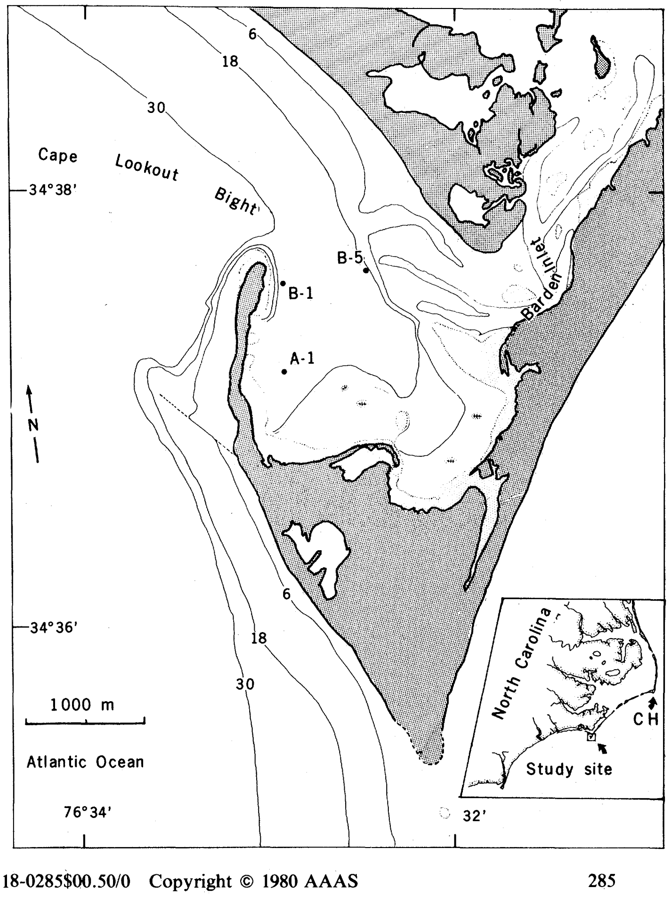

Fig. 1. The Cape Lookout Bight, North Carolina, study site located approximately 110 km southwest of Cape Hatteras (*CH*). Flux studies were conducted at station A-1. Currents at station A-1 are generally < 6 cm sec^{-1} near the bottom and as high as 28 cm sec^{-1} near stations B-1 and B-5 during ebb and flood tide. Depth contours are in feet.

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