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## THE MODERN UPWELLING RECORD OFF NORTHWEST AFRICA

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### ABSTRACT

Several biological and geochemical indicators have been suggested to characterize coastal upwelling processes and to document them in the underlying sediments. These criteria apparently work well in the intensive coastal upwelling regimes off Peru and Namibia. Surface sediments from shelf and slope of the northwest African coastal upwelling area between Cape Bojador, at about 26°N, and the Casamance River, at about 13°N, were examined to evaluate the fate of potential biological upwelling indicators in a moderate upwelling regime. Off northwest Africa no textural upwelling indicators were found in shallow shelf sediments directly beneath the upwelling centers. Due to oceanographic conditions they are rather winnowed out, transported beyond the shelf edge and dispersed on the continental slope by near-bottom currents or grain-by-grain downslope transport. During this transfer, potential upwelling indicators become altered or entirely destroyed by passing through various "filtering" mechanisms. Modern coastal upwelling conditions off northwest Africa are, therefore, not recorded in the underlying shelf sediments and are only badly documented in the adjacent slope sediments. This suggests that simple sediment component analyses may be misleading if used as the only tool to reconstruct paleoceanographic conditions.

### INTRODUCTION

Coastal upwelling systems have for a long time attracted increasing attention as areas of high biological production not only

from oceanographers and biologists but from geologists as well. This interest results from different causes, however; the main geological question is: "Do the sediments underlying an upwelling system reflect the processes occurring in the upwelled water mass by having characteristic facies patterns which can be recognized in the fossil record?" If the answer is "yes", then we would have an ideal tool to reconstruct special paleoceanographic conditions and environments from the fossil record.

The process of coastal upwelling develops when the wind-driven, alongshore surface water currents result in an offshore Ekman transport. This flow is compensated for by transport of nutrient-rich subsurface water into the euphotic layer where optimal light conditions for phytoplankton favor an increasing biological activity. The main characteristics that distinguish coastal upwelling areas from other regions of the ocean are: (1) High nutrient content which causes an enhanced primary production; (2) lowered temperatures at the sea surface; and (3) lowered oxygen content in the surface layer (Barber and Smith, 1981). These upwelling characteristics produce a unique ecosystem, the remains of which should be documented in some way or other in the underlying sediments. The direct relation, however, is strongly complicated by the fact that the upwelling processes are merely short-termed events in the order of days or weeks, including additional seasonal shifts, whereas the sediments show a long-termed memory in the order of hundreds to thousands of years. Depending on the sedimentation rate, only very mixed and averaged oceanographic signals are likely to be preserved in the sediments.

Various sedimentary parameters are discussed in detail as upwelling indicators by Diester-Haass (1978). She suggests that several biological and chemical indicators, like high biogenic opal content, abundant fish debris, low plankton/benthos ratios of foraminifers, presence of cool water foraminifers, high content of organic matter, etc., characterize the sedimentary record of upwelling processes. But, more precisely, such indicators do not stand for "upwelling" alone, but for water masses different from the nearby normal oceanic waters. In fact, these indicators tell us about the temperature, salinity, oxygen or nutrient content, but their individual presence does not necessarily prove that upwelling has occurred.

The main aim of the present paper is to describe the modern sedimentary record along the northwest African continental margin off the Saharan desert in order to detect the influence of the northwest African coastal upwelling system. Mainly, textural parameters and sediment constituents are considered; geochemical aspects, like phosphorite genesis, minor metals and isotope studies, are excluded, as are paleontological species analyses. The investigated sediments come from sample transects across the continental margin between Cape Bojador, at about 26°N, and the Casamance River, at about 13°N (Fig. 1).

## MORPHOLOGICAL SETTING

The shelf in the studied area is generally narrow, about 45-55 km wide, with the exception of the Banc d'Arguin. There the shelf is about 140 km wide and can be divided into a broader, shallow inner shelf with less than 20 m water depth, and a deeper outer shelf area. In both areas the shelf break occurs at water depths of 110-150 m (Piessens and Chabot, 1977).

The continental slope is about 45 km wide with an average inclination of between 2° and 3°. Numerous small and several larger canyons are located off the shelf edge throughout the area, and par-

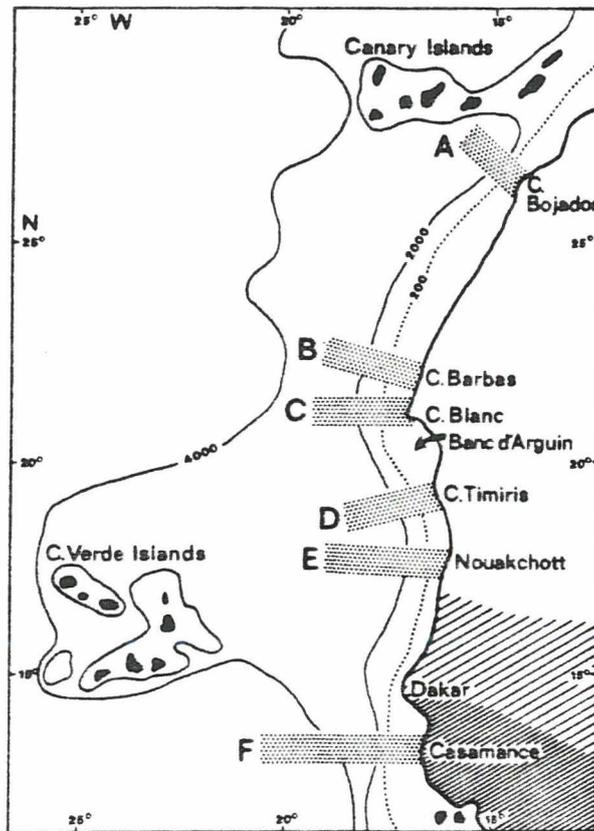


Fig. 1. Northwest African continental margin showing location of investigated sample lines (A,B = "Meteor" cruise 25-1971; C = "Meteor" cruise 39-1975; D,E,F = "Valdivia" cruise 10-3-1975). Densely hatched continental area = winter-dry tropical savannah; widely hatched = winter-dry hot steppe; blank = dry, hot region of Saharan desert.

ticularly south of Cape Bojador (Rust and Wieneke, 1973; Seibold and Hinz, 1974; Arthur et al., 1979), and off the Banc d'Arguin, where one canyon may even be traced on the shelf as well (Bein and Fütterer, 1977). Very fine-grained mud blankets found in some of these canyons appear to indicate that there are no strong currents at present.

#### THE UPWELLING SYSTEM AND OCEANOGRAPHIC SETTING

Off northwest Africa, coastal upwelling is caused by a complex interaction of the nearly longshore Trade Winds and the southward flowing cool Canary Current. The Ekman principle results in a seaward transport of the surface water layer. The nearshore surface layer is replaced by nutrient-rich water masses upwelled from a poleward undercurrent that prevails over the upper slope and at some places on the outer shelf (Mittelstaedt and Hamann, 1981). Upwelling is year round from 20°N to 25°N, and it is most intensive off Cape Blanc (Fig. 2A). Seasonal upwelling occurs during the winter south to Sierra Leone, and in summer farther north up to Morocco and Portugal.

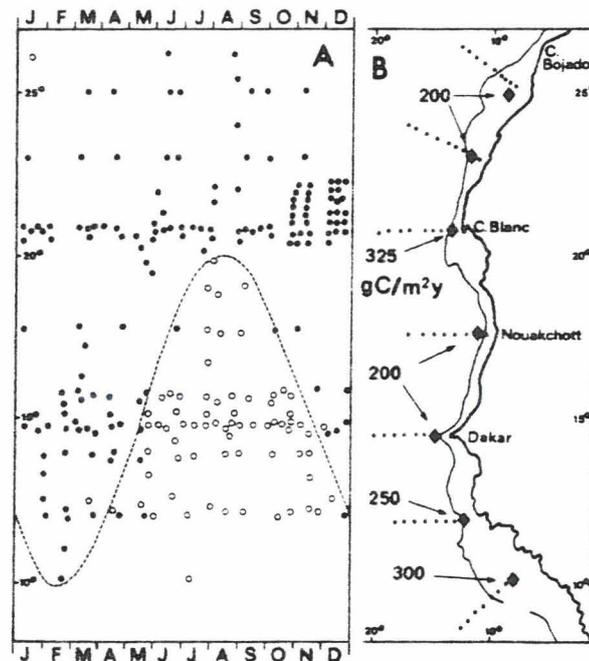


Fig 2. Variation of upwelling off northwest Africa in space and time (A) (dots = observed upwelling at given time) and maximum values for annual primary production (B); simplified from Schemainda, Nehring and Schulz, 1975.

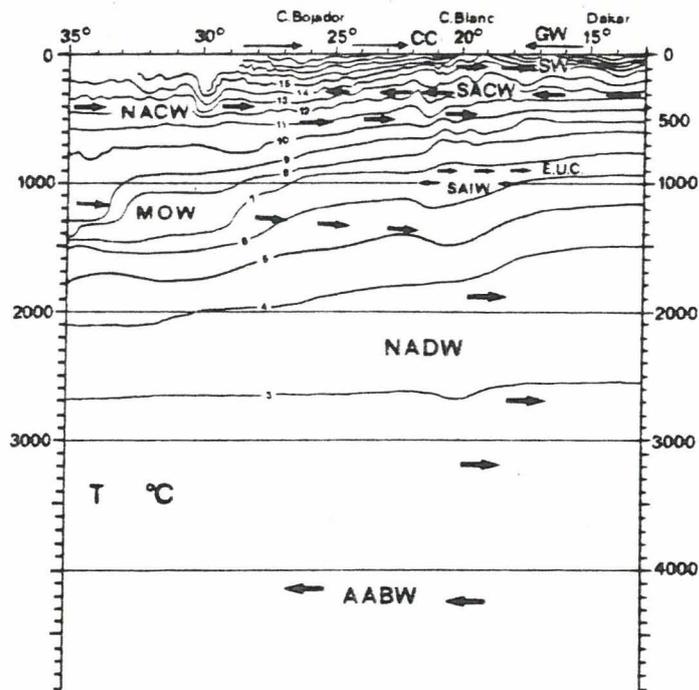


Fig. 3. Stratification of bottom water temperature and ocean circulation (arrows) near the bottom along the northwest African continental margin. AABW = Antarctic Bottom Water, NADW = North Atlantic Deep Water, MOW = Mediterranean Outflow Water, SAIW = South Atlantic Intermediate Water, E.U.C. = Equatorial Undercurrent, NACW = North Atlantic Central Water, SACW = South Atlantic Central Water, SW = Surface Water, CC = Canary Current, GW = Guinea Water Mass; simplified from Lutze, 1980 and Sarnthein et al., 1982; depth in (m).

The maximum values for the annual primary production in that region show a similar pattern (Fig. 2B). Highest values off Cape Blanc coincide with year round upwelling; decreasing values to the south are due to seasonal upwelling. The higher values off Sierra Leone are caused by an additional nutrient input by rivers. The relatively low values north of Cape Blanc can be explained by differences in stratification of the oceanographic circulation system (Fig. 3). Off Cape Blanc, at about 21°N to 23°N, the north flowing undercurrent of South Atlantic Central Water (SACW) provides a characteristically nutrient-rich source water for this upwelling region. North of about 23°N the SACW is replaced by the relatively nutrient poor North Atlantic Central Water (NACW) as the main source for the upwelled waters (Fraga, 1974; Codispoti and Friedrich, 1978). These principal differences in nutrient content of the source waters feeding the upwelling system are most likely the reason for the corresponding regional differences in primary production.

The main area of nearshore upwelling is confined to a water depth in the range of 50 m or less on the middle or inner shelf. However, depending on the strength of the local winds, the upwelling system may extend as far as 100 km offshore, which is twice the shelf width (Mittelstaedt, Pillsbury and Smith, 1975). The system is fed by an onshore compensation flow with water from 100-200 m depth. Strong onshore and alongshore bottom currents result from this compensation flow, preventing the accumulation of fine-grained sediments (Barber and Smith, 1981).

#### SEDIMENT DISTRIBUTION

The upwelling conditions briefly summarized above should be documented in some way or other in the underlying sediments. However, if we look at the sediments on the shallow shelf directly beneath the upwelling area, no indication of the upwelling conditions are observed.

The sediment distribution along the northwest African continental margin is mainly controlled by biological production of skeletal material and by two different mechanisms supplying terrigenous material: (1) an eolian input of carbonate-free or carbonate-poor detritus by Harmattan and Trade Winds respectively, and 2) a fluvial input of fine-grained muds in the southern part of the area by the Senegal River. The overall sediment distribution pattern reflects these predominant supply mechanisms (Fütterer, 1980). A general view of the diverse sedimentary lithofacies present in the surface sediments of that area is given by the carbonate distribution pattern (Fig. 4).

The shelf area off Cape Blanc which is the most productive upwelling area, and the shelf to the north is covered far beyond the shelf edge by coarse, in large part relict, molluscan and algal carbonate sands. Downslope, the carbonate content rapidly decreases to minimum values on the lower continental slope, and increases again on the continental rise. Farther to the south the carbonate content on the shelf decreases as the content of coarse-grained quartz increases. Fine-grained shelf muds are confined exclusively to the pro-delta area of the Senegal River. There is no indication on the northwest African margin of a shallow water mud lens like those reported from the shelf or upper slope of the upwelling areas off Namibia and Peru, respectively. This becomes further evident by a closer look at the grain-size distribution of the sediments. Off Cape Barbas, at about 22°N (Fig. 5), a very coarse-grained sand covers the shelf and extends far beyond the shelf edge onto the upper slope. The sand shows a distinct, continuous shift to smaller grain sizes with pronounced maxima in the silt-size range with increasing water depth. This striking silt-size maximum is even more obvious farther to the south, off Cape Timiris at 19°N (Fig. 6), and off Nouakchott at about 18°N. These areas are located beneath the center of the

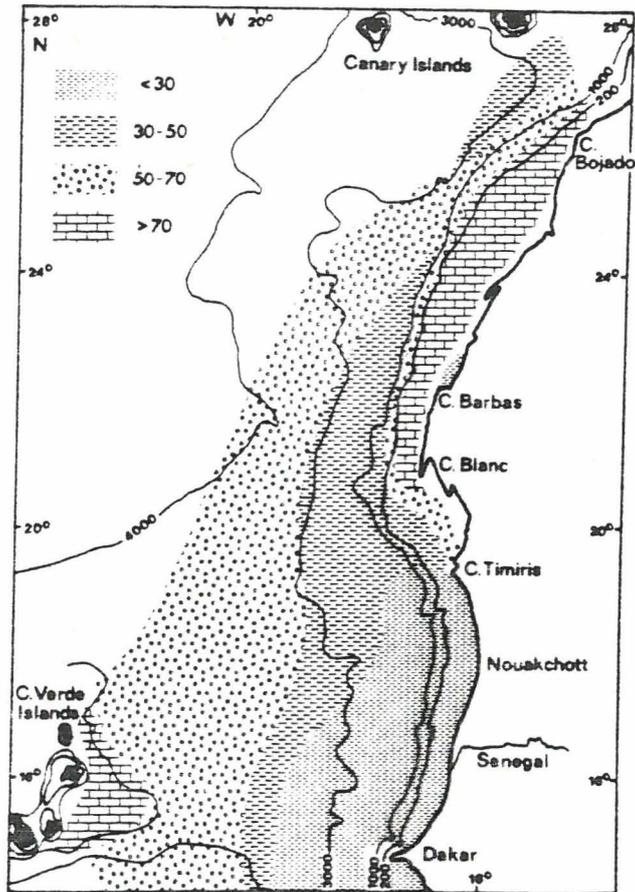


Fig. 4. Carbonate content in weight percent of surface sediments off northwest Africa.

eolian dust supply from the Saharan desert which is assumed to cause this characteristic grain size distribution. There is a sharp decrease in sand content, or a sharp increase in silt content, between 300-500 m water depth south of Cape Blanc, and at somewhat greater water depth of 500-800 m off and north of Cape Blanc. This pattern may be explained by the deflection to the west of the south flowing Canary Current system off Cape Blanc. This current may be deep enough and strong enough to prevent sedimentation of fine-grained material on the upper slope off and north of Cape Blanc, whereas the north flowing undercurrent originating from SACW and centered at 150-400 m water depth shapes the slope south of Cape Blanc.

We interpret the grain size distributions as reflecting oceanic currents and wave action which intensively retard sedimentation on

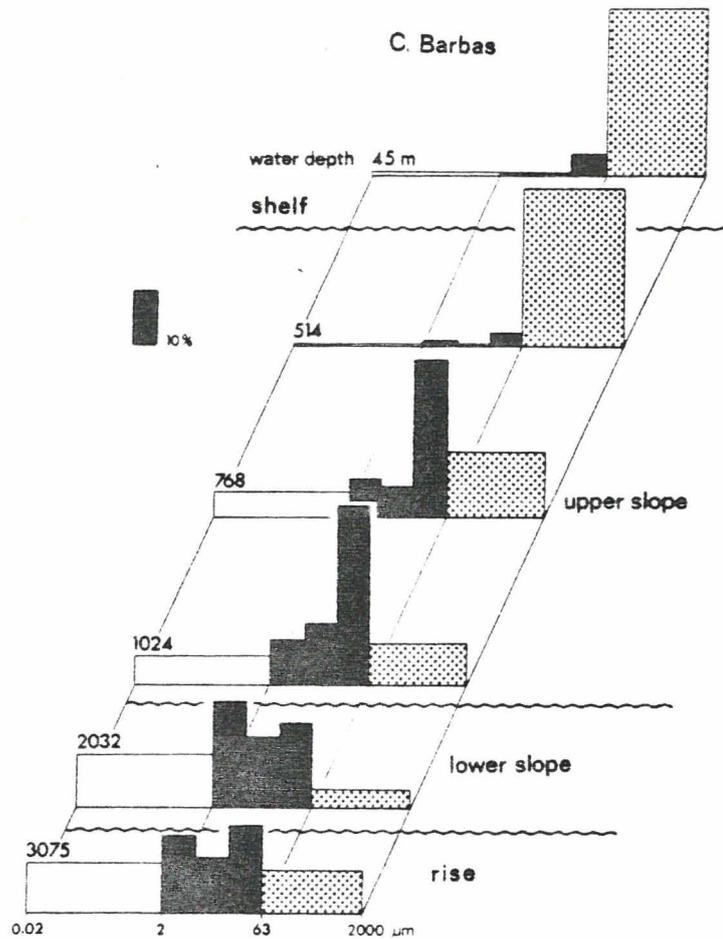


Fig. 5. Grain size distribution of surface sediments off Cape Barbas (sample line B in Fig. 1).

the shelf and upper continental slope at present. These agents may even be strong enough to rework and erode the shelf sediments in places. As a result, a substantial fraction of the sediment supplied to the shelf crosses the shelf edge and is transported downslope in suspension by a nepheloid layer system or grain-by-grain. The latter mechanism accounts for the abundant occurrence of relatively larger shallow water constituents in deeper waters downslope (Bein and Fütterer, 1977; Fütterer, 1980).

At this point we have to state that at present no record of upwelling can be recognized in the modern sediments directly underlying the upwelling area on the shelf and upper slope. All upwelling

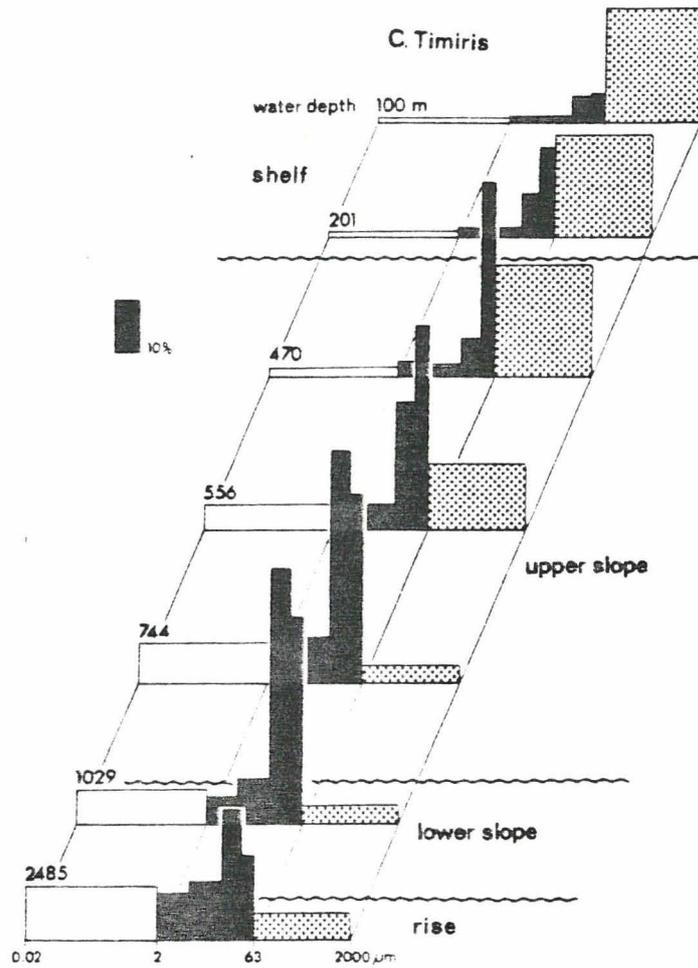


Fig. 6. Grain size distribution of surface sediments off Cape Timiris (sample line D in Fig. 1) showing prominent silt sized maximum caused by high eolian input.

indicators (Diester-Haass, 1978) have disappeared, and for the most part have been transported beyond the shelf edge and spread over the deeper continental slope and rise.

#### SEDIMENT CONSTITUENTS

To trace the shallow water material farther downslope, a quantitative analysis of the sediment components has been carried out by which the conditions described above become evident in more detail

(Figs. 7 and 8). The contrast in carbonate content between the areas off and north of Cape Blanc, and those south of the Banc d'Arguin, is clearly demonstrated. It is caused by different abundances of relict sediment constituents, biogenic carbonate prevailing in the north (Cape Blanc, Fig. 7) and terrigenous quartz dominating south of the Banc d'Arguin (off Cape Timiris, Fig. 8). Benthic carbonates other than foraminifers ("Oc" in Figs. 7 and 8), decrease in quantity from the shelf downslope and consist mainly of molluscs and echinoderms. However, other benthic constituents like ostracods, siliceous sponges, red algae, ascidian spicules, octocorals and boring chips of boring sponges are present as well but in very small numbers only. The last four of these constituents can be used as downslope transport indicators. Depending on their size, these tracer particles are transported downslope to different depths of final deposition. The depth of main deposition is centered at the mid-slope below 1000 m.

As the benthic constituents decrease downslope, the planktonic constituents, mainly foraminifers and coccoliths, increase. The plankton to benthos ratio of foraminifers has been suggested by Diester-Haass (1978) to indicate regions influenced by upwelling. But within the modern surface sediments off northwest Africa, no significant changes in this ratio are apparent.

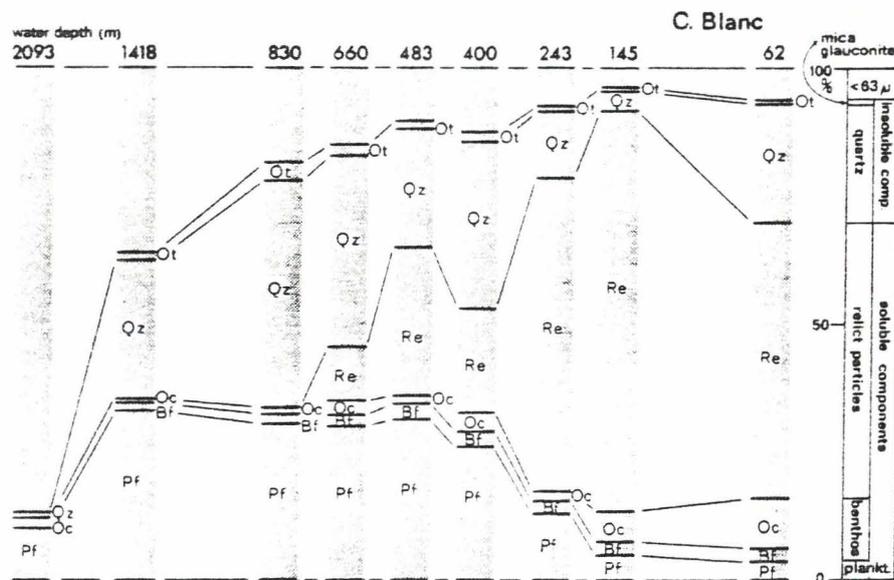


Fig. 7. Composition of coarse-grained (>63 μm) sediment components of surface sediments off Cape Blanc (sample line C in Fig. 1). Pf = planktonic foraminifers, Bf = benthic foraminifers, Oc = other biogeneous carbonate grains (mainly molluscs and echinoderms), Re = relict biogenic material, Qz = quartz, Ot = other terrigenous material (mainly mica and glauconite).

Radiolarians and diatoms occur very rarely in the slope sediments and are not abundant enough to be depicted as compositional units in Figs. 7 and 8. Both of these components are believed to indicate increased fertility. Diester-Haass (1977) found radiolarian to planktonic foraminiferal ratios to be highest in the center of the actual upwelling area off Cape Blanc, and used this ratio to propose increased upwelling during the Würm in this region. The abundance of radiolarian tests in the surface sediments in this area, however, seems to be linked more to the high nutrient content of subsurface waters, and reflects the distribution pattern of the SACW (in contrast to the NACW) rather than to an upwelling process (Labracherie, 1980). Diatom frustules or fragments likewise are extremely rare in the slope sediments and do not show any significant distribution pattern. The low abundance of diatoms in the sediments may be explained by the observation that most of the dominant species living in this upwelling system are only weakly silicified, a fact which favors their dissolution during settling and at the sea bottom (Richert, 1975). A detailed survey on the content of bulk biogenic opal in the slope sediments has been carried out by Koopmann (1979; 1981). As expected, the opaline silica content is very low (Fig. 9) showing relatively higher values nearshore. There is no significant latitudinal variation, although there may be slight maxima off Cape Blanc

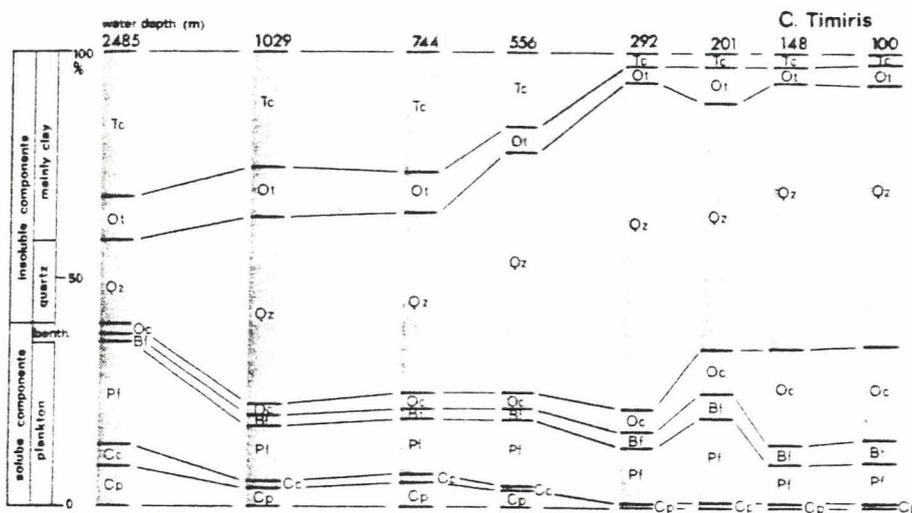


Fig. 8. Quantitative composition of sediment components off Cape Timiris (sample line D in Fig. 1, total sample). CP = <2 μm carbonate particles (derived mainly from coccoliths), Cc = silt-sized coccoliths, Pf = planktonic foraminifers, Bf = benthic foraminifers, Oc = other biogenic carbonate grains (mainly molluscs and echinoderms), Qz = quartz, Ot = other terrigenous material (mainly mica and glauconite), Tc = <2 μm terrigenous particles (mainly clay).

and Cape Barbas, and south of Dakar. With our background knowledge of the existing oceanographic conditions, we might interpret this pattern as upwelling induced off Cape Blanc, and river influenced south of Dakar. However, despite the low abundance of diatoms, fresh water diatoms, e.g., *Melosira granulata* which is a strongly silicified species and well known from eolian dust samples, are relatively abundant here (Fütterer, 1980). This implies that the small maxima of biogenic opal in the area off Cape Blanc reflects the input of eolian dust rather than increased fertility induced by upwelling. In contrast, biogenic opal is abundant in the very shallow and protected Baie du Levrier, on the innermost part of the Banc d'Arguin (Koopmann, Sarnthein and Schrader, 1978). Here the upwelling triggered plankton production from the outer shelf is moved inshore by currents and trapped in a small coastal basin.

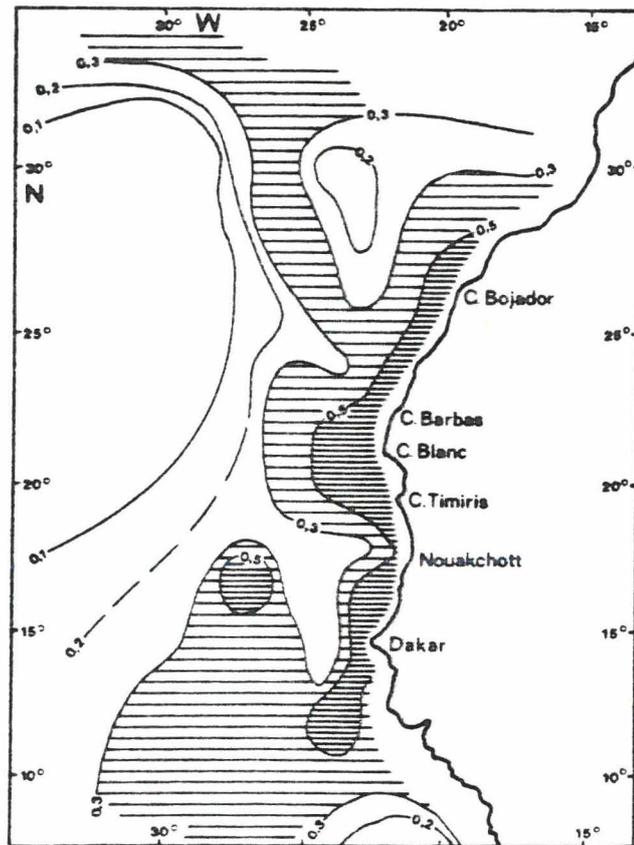


Fig. 9. Concentrations of biogenic opal (weight percent of  $>6 \mu\text{m}$  fraction) in the bulk carbonate-free surface sediments off north-west Africa; modified from Koopmann, 1979.

The pattern of distribution of fish debris, which is another generally accepted indicator for nutrient-rich waters, is like that of diatoms. Fish debris is only occasionally present in the slope sediments, but is enriched in the shallow water of the Baie du Levrier (Koopmann et al., 1978). The organic matter content of the sediments is only a very rough indicator of higher fertility or productivity and, hence, of upwelling. It depends in a complex way on grain-size, sedimentation rate, and organic matter production (Müller and Suess, 1979). On the continental slope off northwest Africa there are two areas of abundant organic matter (Fig. 10): 1) at about 16°N off the Senegal River, and 2) at about 21°N off Cape Blanc, which is the main area of modern upwelling activity. Both areas are at water depths of about 1000 m to 2000 m, which is where the maximum deposition of fine-grained material takes place and forms a mid-slope mud lens. The high organic matter content of this mid-slope mud lens at about 21°-22°N is most probably caused by the coastal upwelling system off Cape Blanc, whereas farther to the south, at about 15°-16°N, it is due to an increase in fertility caused by river input of nutrients. From the distribution of bulk organic matter alone it is impossible to tell which of these two areas is upwelling or river controlled. Better results come from organic geochemistry showing highest marine organic matter contribution (with high H/C ratios) off Cape Blanc, and highest terrestrial organic matter contribution (with low H/C ratios) off the Senegal River, in the mid-slope mud belt (Pelet, 1979).

Other arguments for differentiating between these environments come from textural parameters. The fluvial input of the Senegal River is characterized by a basically bimodal grain size distribution with an excess of clay sizes (Sarnthein et al., 1982), whereas the eolian input off Cape Blanc is dominated by silt sizes. Similar

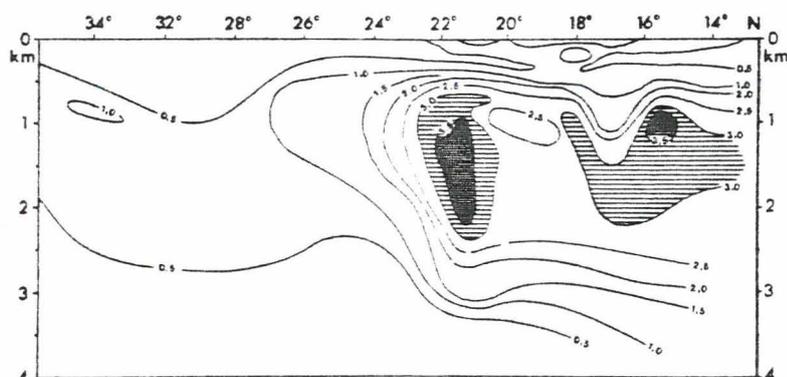


Fig. 10. Distribution of organic carbon (as weight percent) in surface sediments along the northwest African continental margin; modified from Sarnthein et al., 1982.

amounts of organic matter to those in the mid-slope mud lens are found in the fine-grained shallow water prodelta muds of the Senegal River (Domain, 1977), which are associated with considerable amounts of plant debris.

Intensive calcium carbonate dissolution along the continental margin is indicated by the disappearance of pteropod shells with increasing depth (Diester-Haass and Müller, 1979; Fütterer, 1980). The critical depth, assumed to be the aragonite compensation depth (ACD), shallows from 2500 m at the Cape Verde Rise, and from 2000 m on the continental slope off Cape Bojador, to about 500 m approaching the slope off Cape Blanc (Fütterer, 1980). This coincides with increased fragmentation of foraminiferal tests on the slope off Cape Blanc (Diester-Haass and Müller, 1979).

#### CONCLUSIONS

From textural and compositional analyses of the surface sediments underlying the coastal upwelling area off northwest Africa, we can conclude that modern coastal upwelling conditions are not recorded in the underlying sediments of the shelf region.

In comparison with other upwelling areas, such as off Oregon or Peru, where a shallow water upwelling facies is present in the sediments, the unique conditions off northwest Africa become evident. The shelf width and cross-shelf bathymetry (Fig. 11) are such that the poleward undercurrent is centered over the upper slope, only occasionally affecting the outer shelf (Barber and Smith, 1981; Mittelstaedt and Hamann, 1981). During upwelling, the onshore-offshore and alongshore compensation flows originating from undercurrent water masses create strong bottom currents which prevent sedimentation of fine-grained material on the shelf. Because of the steeper shelf gradient off Oregon and Peru, these currents are well above the sea floor in the water column, allowing fine-grained material to accumulate in a shallow water mud lens. Morphological and oceanographic conditions like those of Oregon and Peru today were present off northwest Africa during times of glacially lowered sea level, when the shelf was narrow and the upwelling system was more confined to the shelf edge. Under these conditions a shallow water mud lens could have formed on the upper slope, enabling better preservation and a more complete sequence of geological signals from which a glacial upwelling environment off northwest Africa can be interpreted.

Fine-grained sediments rich in opaline silica, fish debris or organic matter, indicative of present day upwelling, are trapped and preserved only locally in small nearshore basins on the shelf, such as in the Baie du Levrier of the inner Banc d'Arguin. Most of the upwelling-derived material is transported beyond the shelf edge

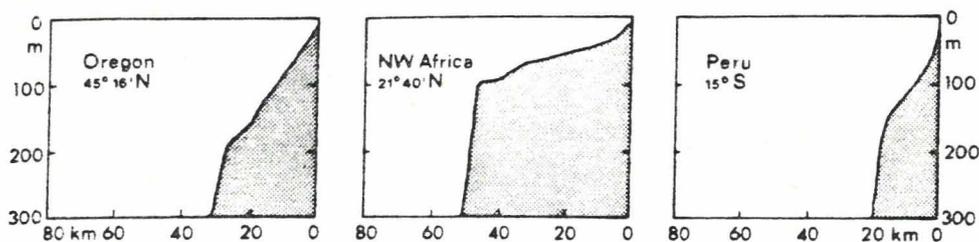


Fig. 11. Cross-shelf bathymetry of the upwelling regions off Oregon, Peru, and northwest Africa; modified from Barber and Smith, 1981. By permission from *Analysis of Marine Ecosystems*, Copyright (c) Academic Press, Inc.

and spread over the continental slope. During this transport the material has to pass diverse filter mechanisms which affect the various components in different ways. Much of the organic matter becomes oxidized, whereas most of the skeletal material is fragmented mechanically during bottom current transport on the shallow shelf or destroyed by dissolution during settling or at the sediment-water-interface. On the slope, the remaining material is transported farther downslope by mechanisms that we do not yet fully understand. Final accumulation takes place in a mid-slope mud lens at water depths below 1000 m. The upwelling "memory" of these slope sediments, however, is weak and in many cases ambiguous (i.e., may be attributed to factors other than upwelling).

From the point of view of the geologists who would like to reconstruct paleo-environments from fossil records, it has to be stated that the textural and compositional signals obtained from the modern slope sediments off northwest Africa are not clear enough to deduce an upwelling environment in the overlying water column without background information from modern oceanography.

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