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The Netherlands Indian Ocean Expedition 1992–1993, first results and an introduction

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INTRODUCTION

The Netherlands Indian Ocean programme was carried out with the RV *Tyro* in The NW Indian Ocean, the Arabian Sea and off Kenya and the Seychelles, during 1992–1993, with the objective "to study the effect, on both spatial and temporal scales, of the monsoon on the climate system in the northern Indian Ocean".

The programme included five research foci, studied in different projects. Project A was directed towards the effects of the seasonally reversing monsoonal system on the coastal ecosystems in Kenya, especially to gain a clear understanding of the physical, chemical and biological processes occurring in the coastal zone. This includes the development of the marine flora and fauna in response to the changing conditions in the coastal zone.

The second project (B) aimed at a study of the dynamics of the pelagic system including a quantification of the carbon flux and biogeographical studies, with the emphasis on distribution and taxonomy of plankton. Part of this project was designed as pilot project for the JGOFS Northwest Indian Ocean study carried out in 1994–95, covering most of the JGOFS core measurements. These studies were planned in close cooperation with the geological project (C), "Tracing a seasonal upwelling system", aimed at determining the spatial and temporal variability of biological, chemical and geological parameters that define an upwelling system, and recognizing these in the sedimentary record as proxies for upwelling in the waters off Somalia and Yemen.

Project D concentrated on two main issues. The first was the late Quaternary productivity and the dynamics of the Oxygen Minimum Zone in the northeast Arabian Sea. The second was the depositional architecture and sediment facies of the middle and lower Indus fan.

The biology of oceanic reef systems of the Seychelles formed the last project (E) within the Netherlands Indian Ocean Programme, and was mainly directed towards biogeographical, taxonomical and ecological studies of the reefs.

The studies comprised within these projects were and are being carried out at a range of different institutes, and preliminary results were discussed at an Arabian Sea workshop held at NIOZ, Texel, the Netherlands from 13–16 February 1995.

The papers in this special form the first group of results from the progamme, and as a consequence, the articles have a strongly variable character. The first paper, by Kromkamp *et al.*, describes temporal and spatial variability of primary production along the Kenyan coast, and their relationship to the development of the cyanobacterium *Trichodesmium*.

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These authors conclude that higher rates of primary production than those measured are likely to occur.

Van Couwelaar studied the spatial and seasonal variations of mesozooplankton, macrozooplankton and micronekton in the SW and NE monsoon in the southern Red Sea, the Gulf of Aden and in the Somali Basin. He found no significant difference in the northern Somali Basin in the mean mesozooplankton biomass in the two periods, which was possibly caused by undersampling the small-sized herbivorous zooplankton.

"Bacterioplankton and nanozooplankton abundance and production off Kenya" (Goosen *et al.*) shows that production estimates decrease with depth and distance from the coast, and that growth rates of bacteria and nanoflagellate abundance are higher in the inter-monsoon period, indicating higher turnover than during the SE monsoon. The increased production of bacterio- and phytoplankton and the higher abundance of nanozooplankton are considered indicative of an increased carbon flux through the microbial loop.

Van Couwelaar *et al.* describe the distribution and life cycle of the swimming crab *Charybdis smithii* in the NW Indian Ocean, a species with a distinct one-year life and is shown to be strongly linked to the monsoons.

Bak and Nieuwland provide details on the seasonal variation in bacterial communities of deep sea sediments from the Arabian sea, and Duineveld et al. compare benthic respiration, biomass and phytodetritus of the Yemen/Somali continental margins with the margin off Kenya. Their original hypothesis that the upwelling region is a site of intensified benthic activity and high biomass due to enhanced productivity, however, could not be verified, as benthic standing stocks in both areas were similar. Strong benthic-pelagic coupling was observed at the northernmost Kenyan offshore transect.

De Wilde and Helder present data on the occurrence of N_2O in the watercolumn of the Somali Basin and its emission to the atmosphere. They reach the remarkable conclusion that emissions reach maximum values of 260–500 $\mu mol\ m^{-2}\ d^{-1}$, three orders of magnitude above the global mean oceanic N_2O flux.

Farrenkopf *et al.* studied the iodine chemistry in the watercolumn of the Northwest Indian Ocean and compared their results with those from other systems, such as the Black Sea and Chesapeake Bay. Although the data and the responsible processes are similar, results from the Northwest Indian Ocean are contrasting by the presence of both iodide and oxygen, indicating that the system is not in equilibrium with the prevailing redox condition and that traditional thermodynamic considerations do not appear applicable.

Theberge *et al.* studied the existence of free and metal-complexed sulfide, especially in the oxygen minimum zone of the Arabian Sea, and found that although free hydrogen sulfide originating from sulfate reduction could not be detected , sulfides complexed to metals were present at levels of up to 2 nM.

Settling, dissolution and burial of biogenic silica in sediments off Somalia on the basis of results from sediment traps, boxcores and modeling of porewater profiles are described by Koning *et al.* It is shown that less than 10% of the biogenic siilica arriving at the seabed of the Somali Margin is buried in the sediments, with a lower burial efficiency than reported from the open Arabian Sea. The particulate fluxes of biogenic silica on the Somali upper slope show strong contrasts between the non-upwelling and the upwelling season, while in the Somali Basin fluxes are lower and show less seasonal difference.

From their study on early diagenetic processes in sediments of the Oman Margin Passier *et al.* conclude that post-oxic diagenesis dominates in these Holocene sediments and that only minor amounts of reduced sulfur species are detected despite the low oxygen concentrations in overlying bottom water. Thus it appears that no significant sulfate reduction occurs, leading to preservation of a large part of the organic matter.

Zonneveld extensively describes the occurrence and distribution of dinoflagellate cysts in surface sediments of the Arabian Sea, and compares their distribution with the characteristics of the overlying water column. The main variation in cyst association appears to be related to variations in temperature and salinity gradients caused by the SE and NW monsoon variability. Four groups can be recognized. Downcore occurrences of species have potential as indicators for paleomonsoon intensity.

The studies of Sonzogni *et al.* relate coretop alkenone indices to sea surface temperatures in the Indian Ocean, showing that Uk 37 values are linearly correlated with SST (5–30°C), with a best fit obtained using SST from 10 m depth at times of highest seasonal productivity.

Rostek *et al.* have used C37 alkenones to estimate sea surface temperatures and productivity over the past 240 kyr in two piston cores form the Arabian Sea. They show that in the SE Arabian Sea glacial stages correspond to relatively high productivity, and warmer interstadials with lower productivity. All time series of productivity proxies appear to be dominated by a cyclicity of 21–23 kyr, corresponding to the insolation precessional cycle. By contrast the upwelling region of the western Arabian Sea appears more complicated.

As the majority of the results described in this issue refer to the NW Indian Ocean upwelling system, and many of the data collected have not yet been described or published, we include below some of these unpublished results, mainly restricted to cruises from the Somali and Yemen upwelling areas, to provide a more detailed background of the area.

Hydrography

During the cruises of projects B and C, held during both upwelling and the non-upwelling periods, the relatively undocumented monsoon-induced upwelling areas off the coast of eastern Yemen and in the NW Somali Basin were studied to establish the contrast between August (peak of the SW Monsoon) and February (NE Monsoon) in both areas. Observations of watermass characteristics, nutrient contents, oxygen concentrations and suspended matter contents were made by CTD lowerings, and subsequent, onboard nutrient and oxygen analysis at stations along two tracks perpendicular to the coast off Yemen, a track off NW Somalia, and one between Cap Guardafui and Socotra. In addition to these results, additional data derived during projects B and D were used. More extensive data and methods are given in the various cruise reports (Baars *et al.*, 1995; Van Hinte *et al.*, 1995; van der Linden and van der Weijden, 1994). Some typical results are given below.

Surface waters

The upwelling in both areas was indicated by low temperatures and high nutrient concentrations in narrow zones along the coasts. Along the Somalian coast the temperatures were lower and the nutrient concentrations were higher in July (Baars, 1994) than in August. Table 1 shows the extreme values for surface waters along the Somalian and eastern Yemen coasts.

The high nutrient concentrations from 7 to 11°N along the Somalian coast are very similar to those given by Smith and Codispoti (1980), but at 5°N no low temperatures (Wiebinga *et al.*, 1997) nor high nutrients were found in July 1992 (Fig. 1). Enhanced

Table 1. Lowest temperatures (°C) and highest nutrient concentrations (μM) in surface waters, 20–29 July 1992 (Somali coast) and 15–20 August 1992 (eastern Yemen coast)

Area	Temperature	PO_4-P	NO_3-N	H_4SiO_4
Somalia	17.3–19.6	1.37–1.63	17.6–20.3	11.7–16.1
Yemen	20.1–21.1	1.63–1.84	17.4–19.4	10.4–15.4

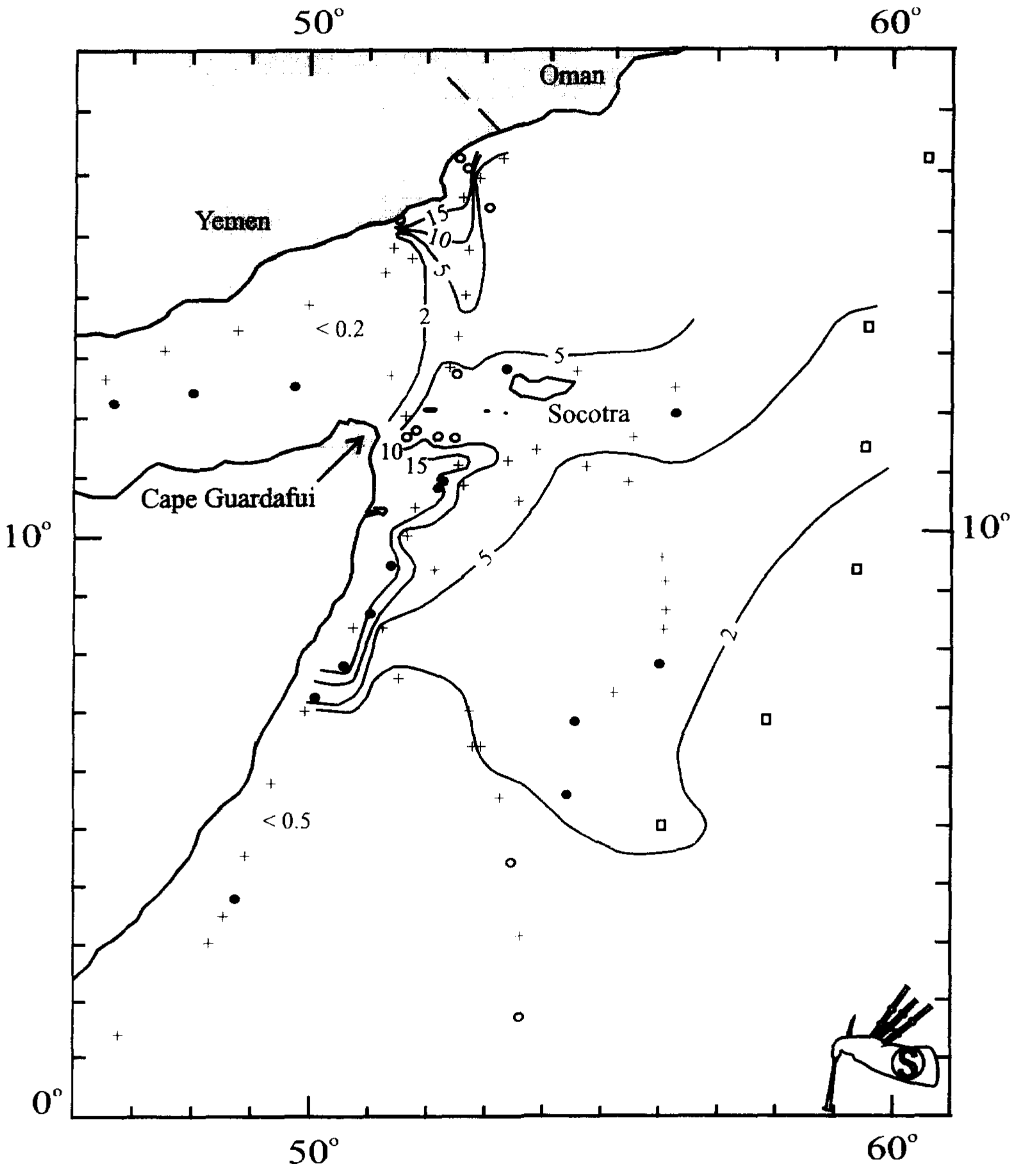

Fig. 1. Concentration of nitrate (μM) in surface water during the summer monsoon, 1992. Stations 17 July to 3 August (●): Stations 15–31 August (○): Stations 12–19 September (□). Pump samples 15 July to 30 August (+).

nutrients in surface waters apparently occurred from mid-July to mid-September 1992, carried by the Great Whirl to at least 500 km offshore, also reaching north of Socotra and into the Arabian Sea. In February the concentrations of nitrate in surface waters were below 0.2 μ M, but in January (Baars, 1994) the surface nitrate concentration was 0.8–1.1 μM in the NW Somali Basin.

In August the oxycline off the Yemen coast was much shallower (<20 m) than off the Somali coast (80–90 m). From the end of July the deep surface mixed layer off the Somali coast decreased primary productivity, because the photic zone was shallower than the mixed layer (Veldhuis *et al.*, 1997), which contributes to the offshore transport of nutrients.

Deeper layers

Salinities down to 1150 m (nearly the total water column) were up to 0.5 PSU higher in February 1993 than in August 1992 at a station between Cap Guardafui and Socotra (Fig. 2), while oxygen was lower during February than during August in nearly the entire Oxygen

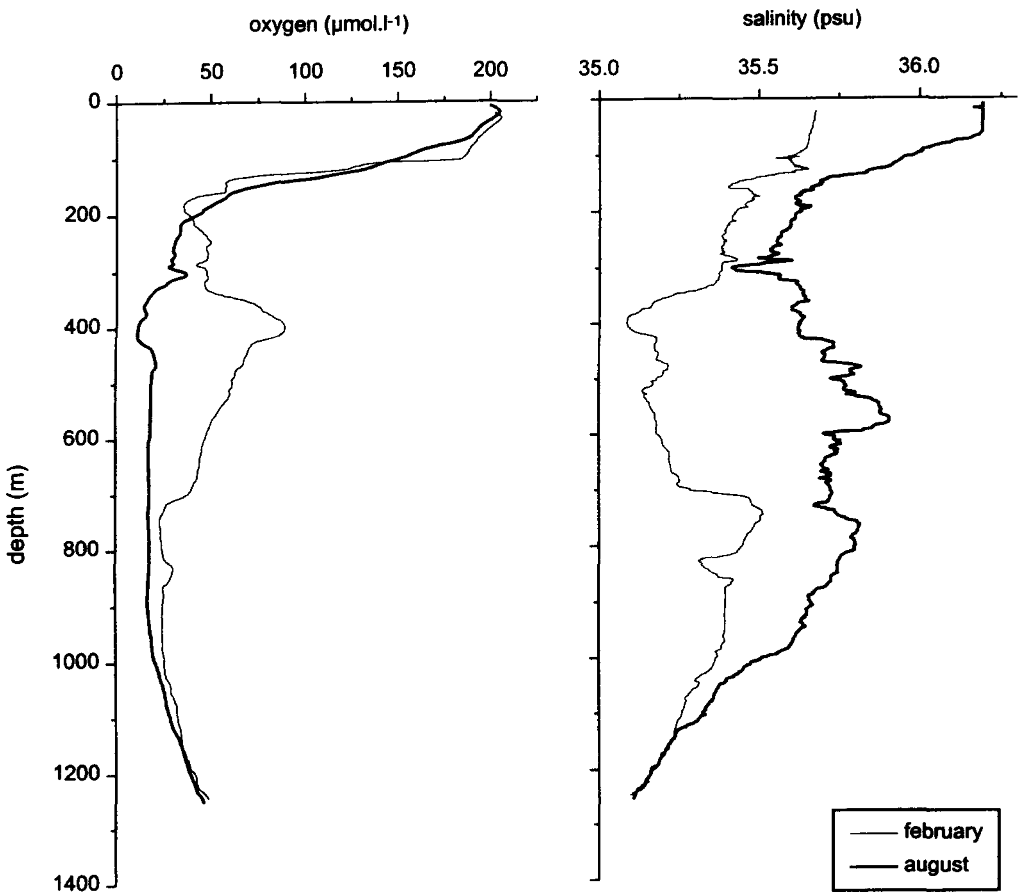

Fig. 2. Profiles of oxygen and salinity at the same position (11°39'N; 52°21'E), occupied in August 1992 and in February 1993 in the gap between Socotra and Cap Guardafui.

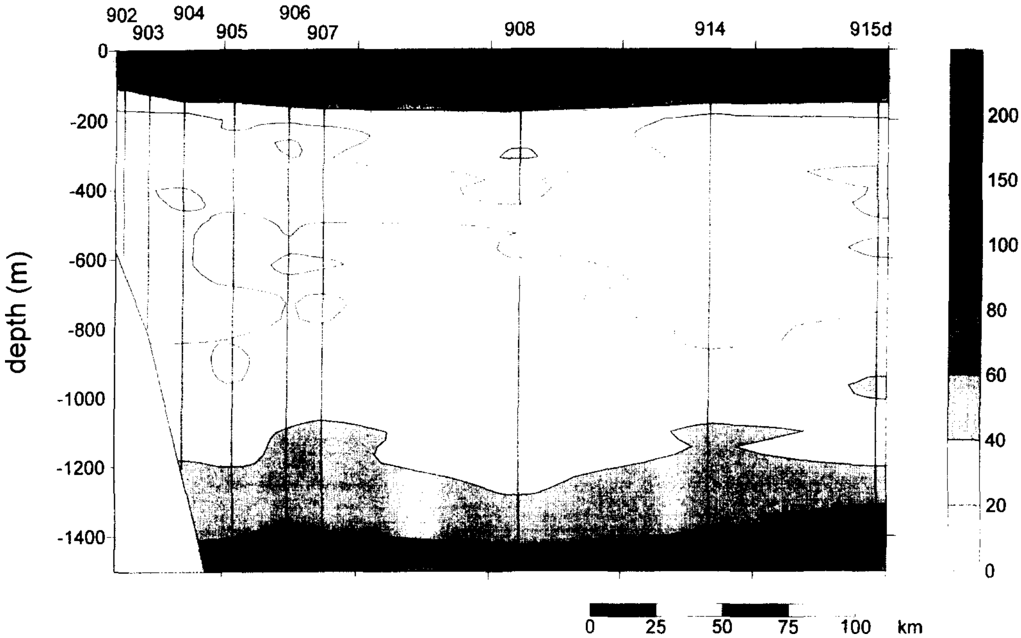

Fig. 3. Oxygen section in February 1993 along 10°47'N in the NW Somali Basin (values given in μM). Interpolated from calibrated CTD downcasts.

Minimum Zone (OMZ). In August the subsurface oxygen concentrations reflected the salinity profile; in February the relation between oxygen and salinity was less clear. A section measured in February along a transect about 100 km to the south (Fig. 3) shows that the oxygen values were <20 μM from 200 to 800 m depth in the OMZ; extremes in the eastern part of the section were < 10 μM at 270 m depth. This section could not be measured in August due to strong winds, but 100 km to the north, the oxygen content never fell below 20 μM.

The fact that the subsurface oxygen concentration is lower during the unproductive NE Monsoon than during the productive period is surprising, suggesting a substantial exchange of deep water through the gap between Socotra and Cap Guardafui, confirming the recent results of Fisher *et al.* (1996). The role of exchange of waters from the south in maintaining disoxic conditions in the Arabian Sea was stressed by Olson *et al.* (1993); the region west of Socotra apparently plays a vital role in this exchange.

In the region around Socotra the oxygen concentrations, especially in the shallow oxygen minimum zone between 200 and 300 m depth, with concentrations of 6–20 μM, were much lower than the value of about 1 ml L^{-1} (44 μM), given in Wyrtki (1971). This layer is often quite thin and might be missed when sampling at standard depths.

The contrast between August and February for the eastern Yemen section is most clear in the shallow subsurface oxygen distribution (Fig. 4). In August the oxygen concentration is <30 μM at about 20 m depth at stations in the middle of the section, and except for the outermost station, a substantial undersaturation was found at 3–4 m depth. The shoaling of low oxygen water was much more pronounced than given by Currie (1992).

In February the surface mixed layer, saturated with oxygen was about 40 m deep. The lowest subsurface oxygen minimum concentrations (2–4 μM) were found in February at

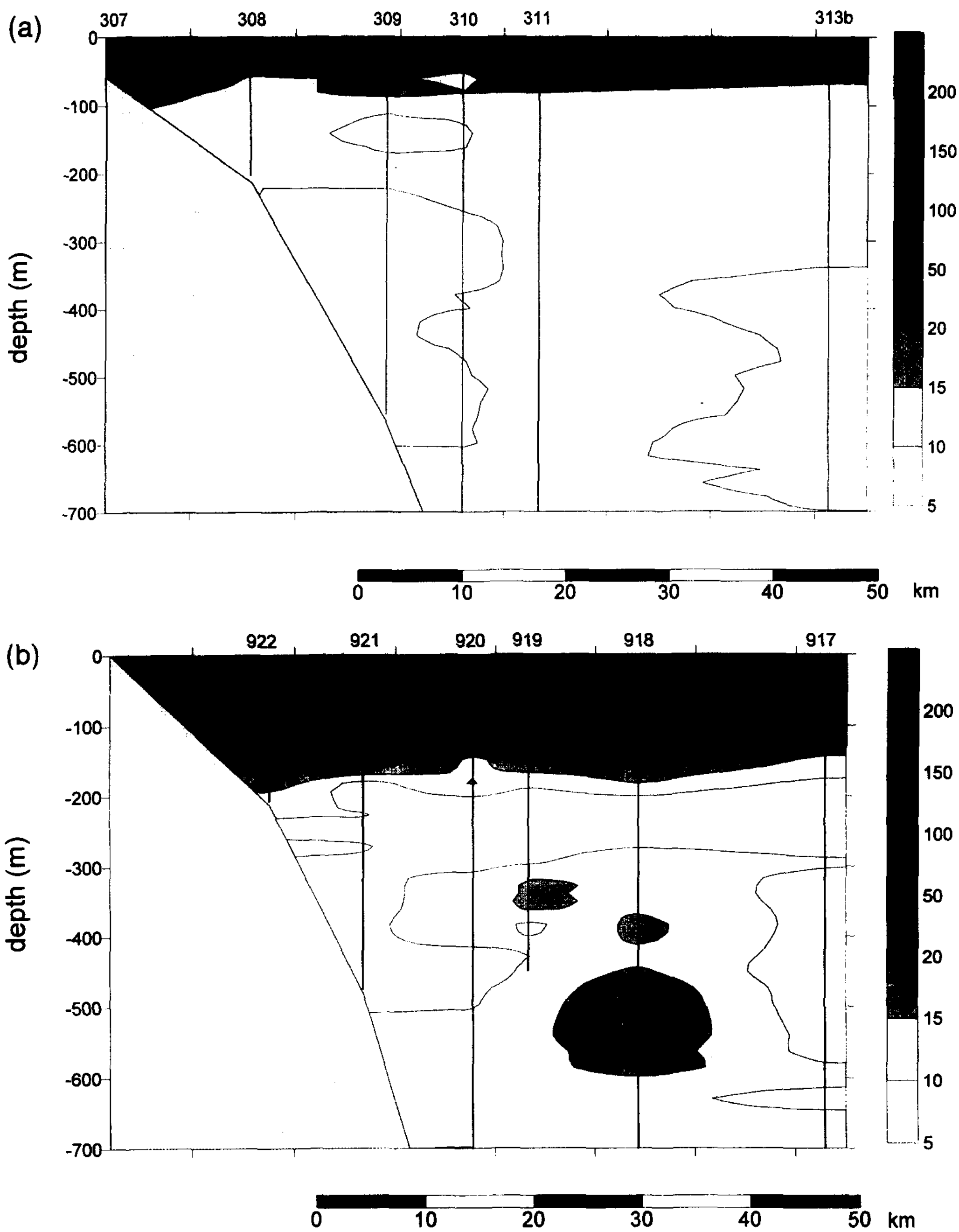

Fig. 4. Sections of oxygen along about 16°N off eastern Yemen in August (a) and February (b). Interpolated from calibrated downcasts. The low concentrations at the surface of station 917 are probably caused by malfunctioning of the sensor; neither the upcast nor the Winkler calibrations showed these low values.

about 230 m depth in thin layers associated with salinity maxima between 35.90 and 36.00 PSU and σ_θ of 26.55, suggesting Persian Gulf Water (PGW; Wyrtki, 1971; Currie, 1992). The shallow oxygen minima in this area were not associated with a σ_θ of 25.8 as stated by Wyrtki (1971). The intermediate oxygen maxima between 350 and 550 m depth have about 35.75 PSU at σ_θ of 26.85 and are not associated with a characteristic water mass.

In August the watercolumn had less structure in oxygen and salinity; no clear indications of PGW were found. The minimum oxygen concentrations during the unproductive season were also lower than during August (> 7 µM), although the contrast was not as large as near Socotra.

Differences in oxygen minima are thought to originate from displacement of water masses, rather than from oxygen consumption by locally settling particles. The oxygen minima do not originate from the Persian Gulf, but are associated with PGW, passing through areas with high productivity (Olson *et al.*, 1993). No nitrite maxima were found associated with the oxygen minima.

Particulate fluxes

Two arrays with sediment traps and current meters were moored in 1992 on a transect across the Somali ocean margin (Fig. 5) to determine the nature and fluxes of settling particulate matter within a nearly 9 month interval spanning the SW to NE Monsoon, until their recovery in mid-February 1993 (Brummer, 1995). The traps should allow for assessing

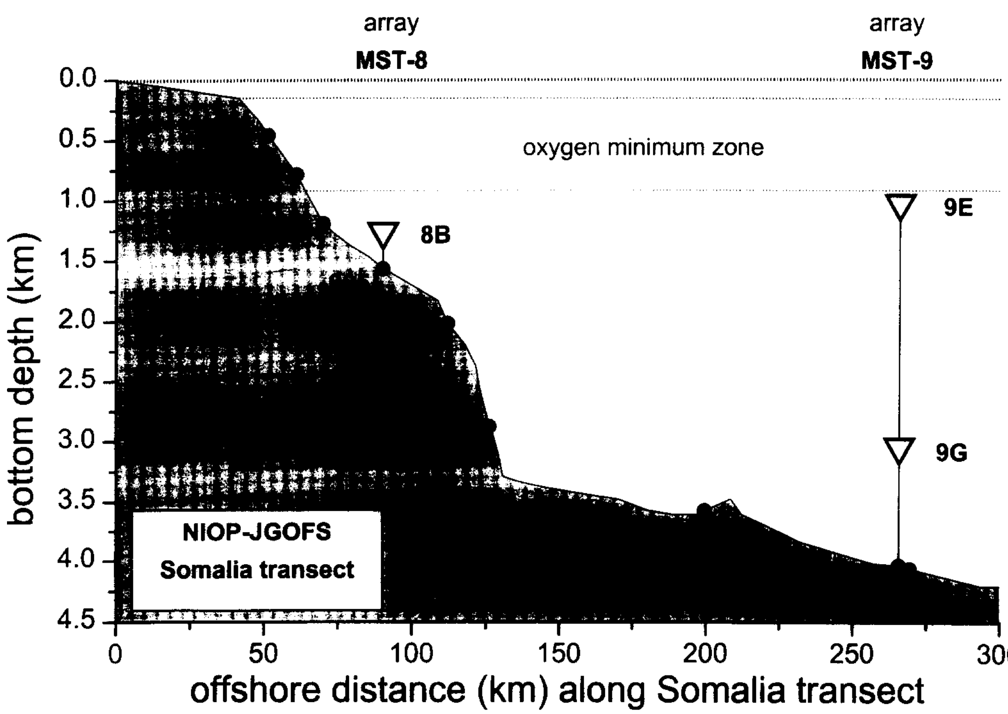

Fig. 5. Profile of section at the Somali margin with sample stations for water-column and bottom sampling (black dots and number) as well as locations and positions of sediment trap moorings (after Brummer *et al.*, 1995).

the differential contribution of particles settling out of the euphotic zone and those transported 'laterally' over the continental slope.

Array MST-8 was deployed within the region of active coastal upwelling during the SW Monsoon on the Somali continental slope (10°45.444′N/51°56.655′E) at a bottom depth of 1533 m with a sediment trap at 1265 m depth, i.e. 268 m above the seafloor. Array MST-9 was moored outside the region of coastal upwelling proper, in the deep Somalia Basin south of Socotra (10°43.068′N/53°34.422′E) at a bottom depth of 4047 m with traps at 3047 and 1032 m depth, i.e. at 1000 and 3015 m above the seafloor, respectively. All traps started sampling on 7 June, 1992, in synchronized one- or two-week intervals until completion on 14 February, 1993 (Fig. 6).

Current velocities were generally below 15 cm sec^{-1}, although up to 20 cm sec^{-1} in rare instances. Inclinations were within 9° of the vertical, indicating that particle flux sampling was not seriously biased by hydromechanic interference throughout the deployment period.

Total mass fluxes settling towards the Somali slope are dominated by a pronounced maximum in October 1992 of up to 4340 mg m^{-2} day^{-1}, which is characterized by the highest proportion of $CaCO_3$ (69.6%) compared to the other collecting periods covered by trap MST-8B (Fig. 6). Although the mass fluxes of organic matter and biogenic opal were the highest as well (180 and 404 mg m^{-2} day^{-1}, respectively), their proportional contributions were the lowest measured (4.8% and 10.7%).

Analyses of the material show a pronounced flux of assorted species of small benthic foraminifera, ostracoda and bivalves as well as fragments of sessile calcareous biota derived from the inner shelf to uppermost slope (S. Conan and S.R. Troelstra, pers. comm., 1997). These provide direct evidence for resuspended sediment as the main source for the massive flux intercepted 268 m above the Somali slope in October. Its temporal occurrence on the Somali slope coincides with the end of the SW Monsoon as is also indicated by a marked change from upwelling-supported to non-upwelling-supported ratios of stable nitrogen isotopes. Possibly the changing circulation caused by the waning SW Monsoon (Schott *et al.*, 1990) may have triggered the resuspension of sediment material at the shelf break.

At other times, the contribution of resuspended sediment to the mass flux on the Somali slope is lower by at least 3 orders of magnitude. A different mode of lateral advection, i.e. by surface currents carrying bottom-derived material offshore in suspension, is suggested by the presence of benthic and epiphytic diatom frustules that occur in trace amounts in all traps, particularly during the SW Monsoon (van Iperen, pers. comm., 1997). Both mooring sites were close to or overrun by large gyres such as the Great Whirl that transport large quantities of coastal upwelled water offshore at velocities of up to 3 m sec^{-1} (Fischer *et al.*, 1996).

Excluding the sediment-derived contribution, total mass fluxes to the Somali slope amount to 215 g m^{-2} $year^{-1}$, about 2–4 times higher than those in the deep and shallow Somali Basin, respectively (Fig. 6). On an annual basis the estimated total mass flux in the deep Somali Basin (MST-9G) is about 80 g m^{-2} $year^{-1}$, similar to the highest annual values reported from the same depth in the Arabian Sea (i.e. 76 g m^{-2} $year^{-1}$ for 1990: Haake *et al.*, 1993). In all traps fluxes are highest during the SW Monsoon (about June to October), attaining the lowest values in November–December during the SW–NE intermonsoon, increasing again in January–February during the NE Monsoon (Fig. 6). Following the onset of coastal upwelling and the development of the Great Whirl–Socotra Gyre system in late May 1992 (de Bruin, 1994), upwelling supported organic matter fluxes first arrived almost simultaneously in all traps in late June as shown by nitrogen stable isotopes. On the Somali slope they persisted almost without interruption into October, whereas in the Somali

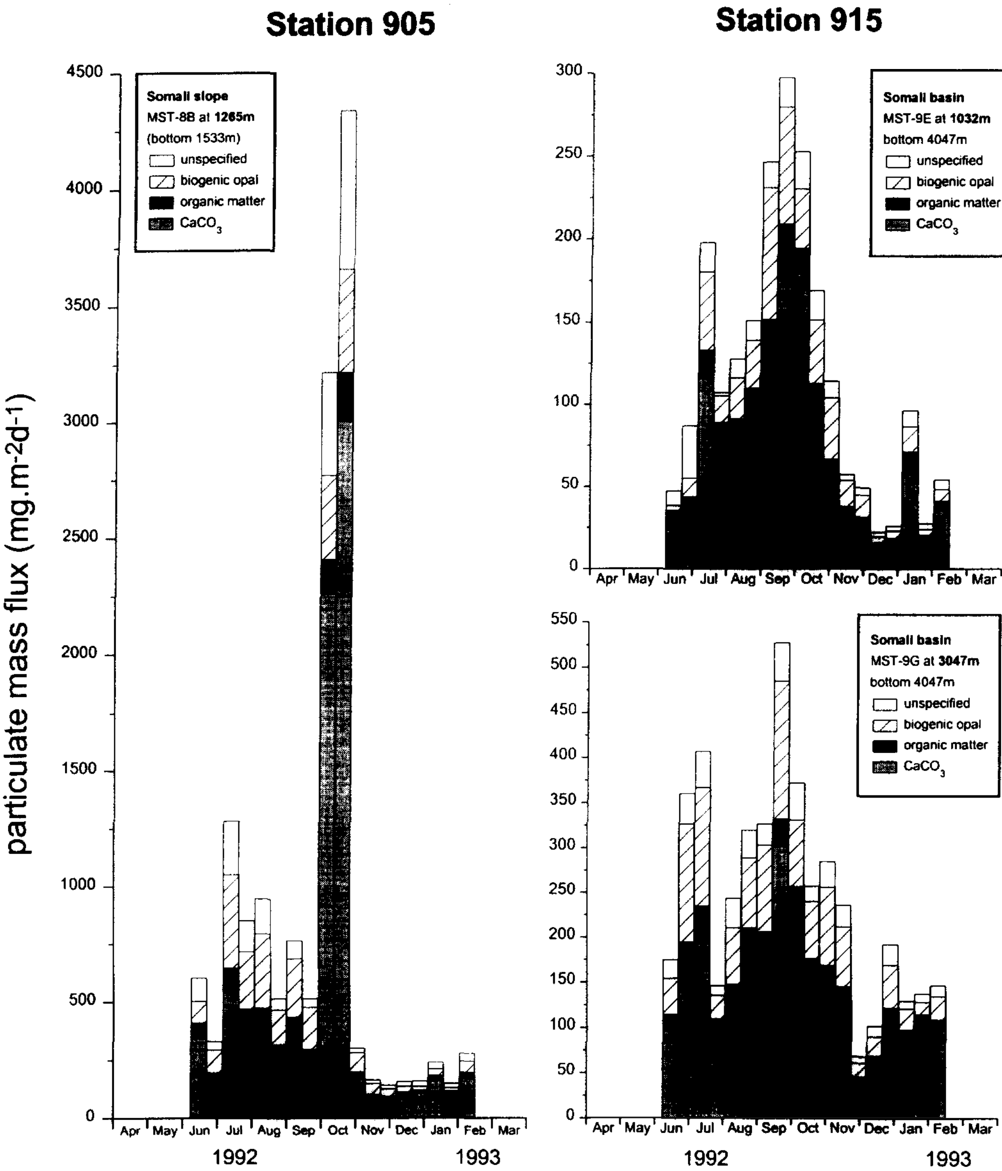

Fig. 6. Particulate mass fluxes and their composition for traps at the Somali margin. For trap numbers see text and Fig. 5.

Basin they were interrupted during mid to late July and also ended earlier, by mid September. In general the mass fluxes of major constituents, i.e. $CaCO_3$, biogenic opal and organic matter, covary strongly with time, although their proportional contribution to the total flux does change. Most variation is shown by the proportional contribution of biogenic opal, which is enriched in the total mass flux during the SW Monsoon, particularly on the Somali slope (Koning *et al.*, this volume).

Benthic boundary layer dynamics.

At the Somali continental margin a benthic lander (BOBO) was deployed to determine if, and to what extent, lateral advective near-bottom sediment transport occurs at the upper continental margin, i.e. below the site of the shallowest trap array (station 905, see Fig. 5). Details of the equipment and the calibration are given by van Weering *et al.* (in van Hinte *et al.*, 1995). Deployment was on 4/06/92 at position 10°46,206′N/51°56,981′E, at a waterdepth of 1535 meters.

Preliminary results of the current velocity recordings from 4 June–7 July, 1992 show a semi-diurnal tidal effect, near-bed current velocities were up to 12 cm sec^{-1}, the currents above 5 cm sec^{-1} being generally associated with a dominant flow to the north and northeast. Maximum current velocities consistently coincided with a drop in near-bottom water temperature of 0.4°C. There was little difference in current velocities measured at 25 cm or at 50, 75, or 100 cm above the bottom.

The associated bottomwater temperature data show that if the flow is directed to the SW for some time, this results in higher bottom water temperatures, with a maximum difference of 0.75°C; northeasterly flow results in lowering of bottom water temperatures, westerly or southwesterly flow in transport of waters with higher temperatures. Apparently along-slope directed currents dominate sediment transport at site 905, introducing the laterally derived sediments into the traps, as indicated above.

Sediments and sedimentation

An overview of sediments collected in the NW Indian Ocean and Arabian Sea until the 1970s is provided in the Geological-Geophysical Atlas of the Indian Ocean (1975), including the results of the International Indian Ocean Expedition (1959–1965). Since then a considerable number of papers dealing with sediments and sedimentation have appeared, with a focus shifting from largely descriptive, to the recognition of the importance and effects of upwelling along the margins of the northern Indian Ocean, via preservation of carbon in the sediments and its relationship to bottom water conditions to the realization of the effects of climatic change and the governing mechanisms and the variability of these in time.

Kolla *et al.* (1976, 1981) described surficial sediments, clay minerals and quartz in the surface sediments of the NW Indian Ocean and Arabian Sea. They showed that organic carbon in surface sediments was highest (locally above 5%) off the Indian margin, presumably due to preservation in low oxygen bottom waters between 200–1500 m depth and high sedimentation rates. The distribution of palygorskite off Somalia and Arabia was considered wind-induced. In a follow-up paper on the geochemistry of surface sediments (Shankar *et al.*, 1987) it was shown that eolian processes and upwelling also were predominant in sediment distribution and properties of the Owen Basin. Haq and Milliman (1984) provided an overview of the marine geology and oceanography of the Arabian Sea and coastal Pakistan, while more recently an overview of Late Quaternary sedimentation in the Gulf of Oman has been presented by Uchupi *et al.* (1997).

Sirocko and Lange (1991) used clay mineral accumulation rates in undisturbed and turbidite-free sediment cores to differentiate between glacial and Holocene wind transport, and showed that during the last glaciation higher abundances of quartz, illite and chlorite in the NW Arabian Sea were contributed by increased dust flux from the Persian Gulf to the Gulf of Oman. Based on the same material, Sirocko *et al.* (1991) showed that the northwesterly winds and the southwest monsoon persisted over the last 27 kyr, but that the glacial seasonal time span was reduced because of a delay in the onset of the southwest monsoon. Recently it was found that the response of the SW monsoon to long-term insolation changes over the Arabian Sea occurred in distinct events of less than 300 years, probably related to albedo changes in Asia (Sirocko *et al.*, 1993).

Recent studies relating the distribution of and relatively high organic carbon contents in sediments of the Arabian Sea, Oman and Yemen margins and off Somalia to increased upwelling-induced seasonal productivity (Pedersen *et al.*, 1992, 1993) and its preservation in the margin sediments to the oxygen minimum zone at depth of 200–1500 m (Paropkari *et al.*, 1992, 1993) yield contrasting views as to the processes responsible for preservation of the organic matter.

Therefore the northwestern Arabian Sea and particularly the Yemen and Oman margins provide interesting sediments for the study of early diagenetic processes. For the Yemen–Oman region, with sediment organic C contents up to 4% (Fig. 7), Pedersen *et al.* (1992, 1993) advocate the "production hypothesis" in which the high organic content in the sediment is thought to be related primarily to the high productivity in overlying surface

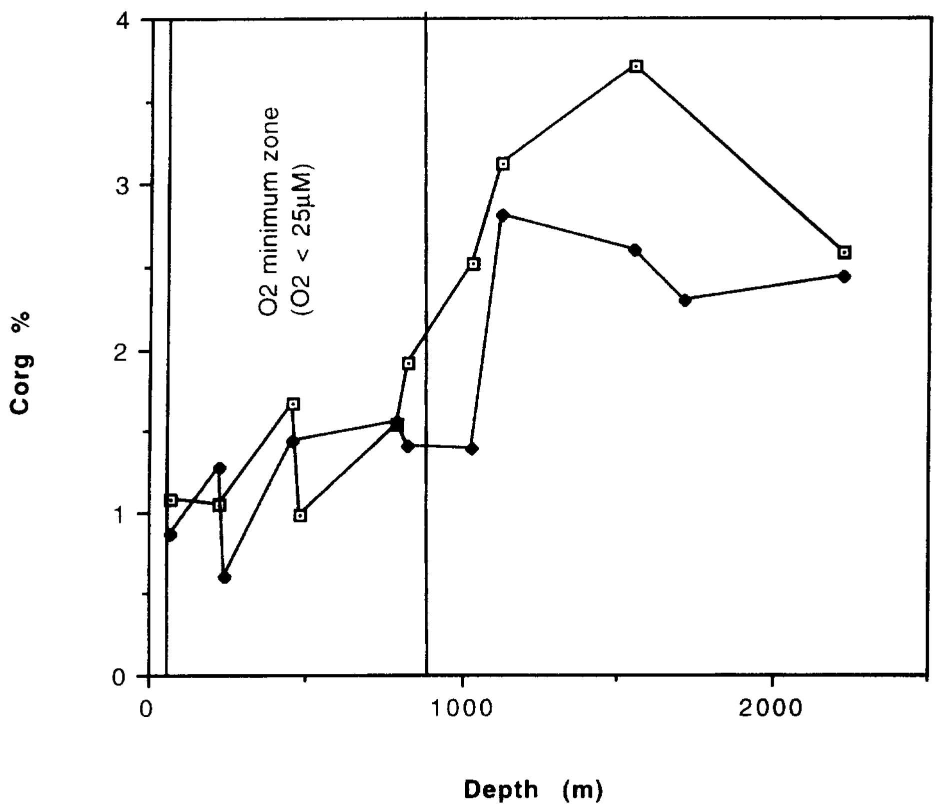

Fig. 7. Content of C_{org} (% w/w) in surface sediment (0–1 cm) as a function of water depth at the Yemen margin. The area where the oxygen minimum zone (O_2 < 25 µM) in the overlying water is in contact with the sediment surface is indicated. Open squares are for cruise C1 (upwelling period) and closed diamonds for cruise C2 (non upwelling conditions). Results from Helder *et al.*, 1995.

waters. In contrast, Parokpari *et al.* (1992, 1993) advocate the "preservation hypothesis" in which high organic carbon content is thought to be directly related to the low oxygen concentrations of overlying bottom waters.

Canfield (1994) concluded that the time of exposure to oxic conditions rather than the oxygen concentration of overlying bottom water itself is most important for preservation of organic carbon in deeper (anoxic) marine sediments. Because organic carbon accumulation, (oxic) degradability of the deposited organic matter, and the oxygen concentration of overlying bottom water determine the thickness of the oxic zone and thus the exposure time to oxygen, these factors are thought to be responsible for the quality of the organic matter arriving in the deeper, anoxic sediment zone and ultimately for the preservation of organic matter.

During the NIOP cruises C1 (August 1992) and C2 (February–March 1993) a relationship beween Corg in surface sediment and oxygen concentration in bottom water was found (Fig. 7) (Helder *et al.*, 1995), supporting the earlier conclusions of Pedersen *et al.* (1992), that highest Corg contents in surface sediments do not coincide with lowest bottom water oxygen concentrations. AMS dating of box cores collected along the Yemen transects during cruise C1 indicate sedimentation rates from 7 to 28 cm/ky and sediment redistribution by turbidity flow processes to be responsible for downslope transport and focusing of fine grained, organic rich sediments at depths below 900 m water depth on the Yemen–Oman continental slope. The organic matter of turbiditic deposits was found to be up to nearly 3000 years older than the actual age of the emplacement of the turbidite (Susanne Heier-Nielsen, pers. comm.).

Pore water profiles of diagenetic indicators for the Yemen transect (Helder *et al.*, 1995) (Fig. 8) show a well established sequence with depth of the utilization of oxygen and nitrate and Mn-oxides as electron acceptors for organic carbon oxidation, but the porewater concentrations of dissolved Mn and dissolved Fe, as well as the concentrations of reactive Mn and Fe, are extremely low. These results are similar to those reported for station NIOP 484 at the Oman margin by Passier *et al.* (1997). Obviously the restricted oxygen penetration into the sediment and the low oxygen concentrations at the sediment–water interface cause inefficient reoxidation of upward diffusing Mn^{2+} and Fe^{2+}, and thus these ions can escape partly to the overlying water column, thereby limiting the potential importance of Mn- and Fe-oxide reduction in organic carbon oxidation (Canfield *et al.*, 1993b).

Another direct consequence of low oxygen concentration in overlying bottom waters is described by Duineveld *et al.* (1997) who found accumulation of caretenoid pigments in the sediments along the Yemen transects, a clear indication of the lack of chlorophyl-a degradation (Sun *et al.*, 1993). The same authors found that during whole-core, on-deck Sediment Oxygen Demand (SOD) measurements, enhanced oxygen concentration in overlying water during the incubations resulted in significant higher SOD values.

Finally, the lack of sulfate reduction in these sediments (Passier *et al.*, 1997) is an extremely important result. Their statement that, "the relatively high amounts of humic sulphur indicate that reduced sulphur is more easily incorporated in the relatively labile organic material in the top of the sediments than in iron sulphides" could be associated with the lack of reactive iron and Fe^{2+} in these sediments, while the incorporation of sulphur in organic matter also reduces its reactivity (Sinninghe Damste *et al.*, 1989).

In summary, the results on early diagenesis as presented in this volume seem to indicate that although highest organic carbon content of surface sediments does not coincide with lowest oxygen concentrations in overlying bottom water. But this does not mean that

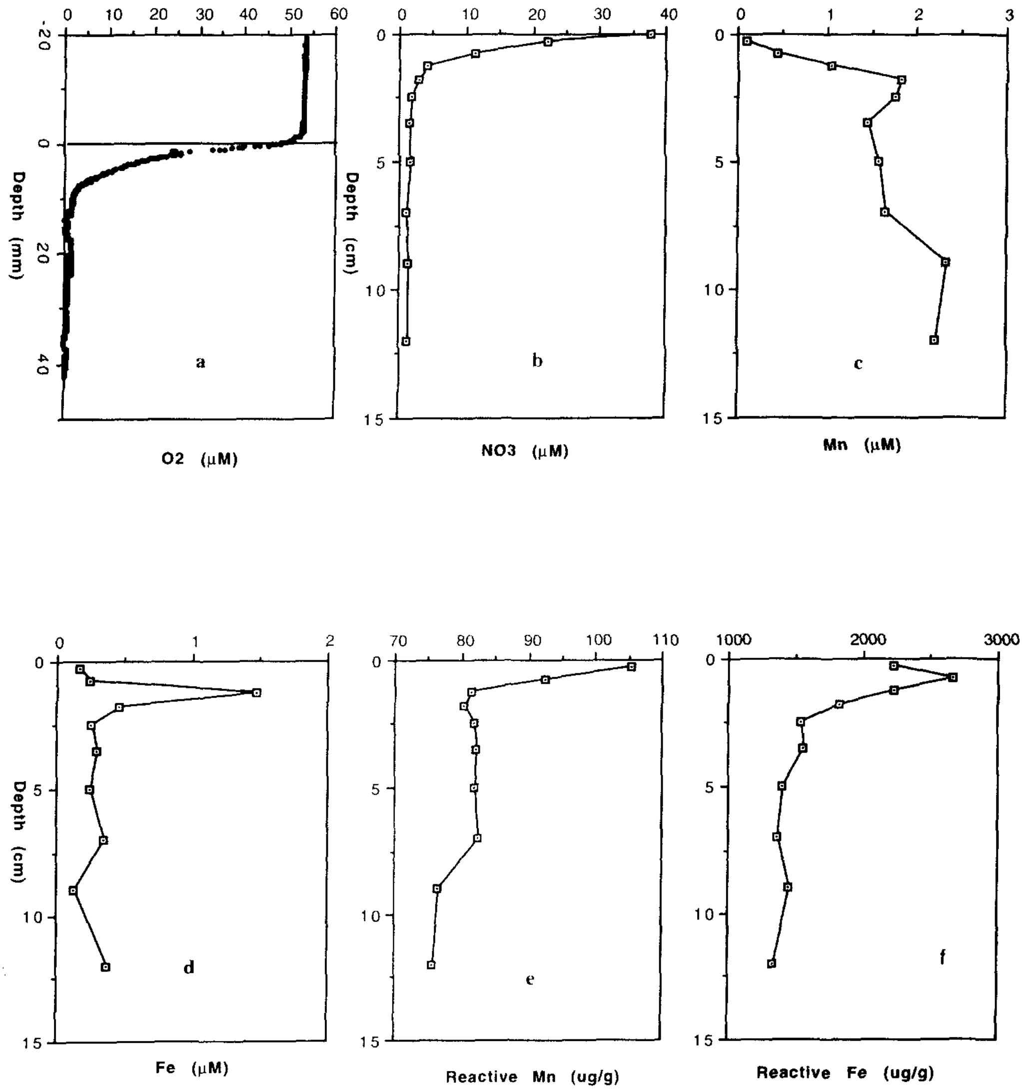

Fig. 8. Pore water profiles of oxygen (a), nitrate (b), dissolved Mn (c), dissolved Fe (d), reactive Mn-oxide (e), and reactive Fe-oxide (f). Note the different depthscale for the oxygen profile which was made by deployment of a profiling lander. Results from station 306, cruise C1. Water depth 1500 m. (Helder *et al.*, 1995).

oxygen concentrations are not important. Firstly, for the rather old and refractive organic material accumulating at water depths > 1000 m, the lack of eposure time to oxygen might very well be an important factor in explaining the lack of anoxic mineralization, such as sulfate reduction. Secondly, the low oxygen concentrations in overlying bottom waters are probably responsible for the restricted role that Mn- and Fe-oxide reduction can play in organic carbon mineralisation. Thirdly, the limited availability of oxygen can cause indirectly formation of a resistant organic sulphur compound.

In a series of papers by Prell and co-workers in the 1980s, and supported by the results of

ODP Leg 117 (Prell *et al.*, 1989) at the Oman margin and Owen Ridge, the fundamental boundary conditions and forcing mechanisms of the monsoonal climatic variability were studied and defined. Follow-up studies (e.g. Anderson and Prell, 1992; Prell and Kutzbach, 1992) discussed the structure of the southwest monsoon winds over the Arabian Sea and the geological evidence for these winds in the Late Quaternary, as well as the implications for the evolution of the monsoonal system.

Off Somalia and off Yemen however, sampling is extremely limited. Only two of the sample sites of Sirocko (1989) are located within the northern Somali Basin. DSDP site 234 was drilled in the southern part of the Somali Basin and stopped 242 m below seabottom, recovering an incomplete sediment sequence, unsuitable for climatic reconstruction.

In 1985 the French MD 44-INDUSOM Expedition collected 21 piston cores from the eastern African Margin and from the Somali Basin (Caulet, 1987) south of Socotra. Of these three cores were located in the northern Somali Basin, between 5 and 10°N. Initial results (Caulet *et al.*, 1988) showed that off Somalia palygorskite increases from 6 to 20% of the clay fraction, indicative of increased eolian influx at this latitude. Recent results (Venec-Peyre *et al.*, 1995; Tribovillard *et al.*, 1994, 1996) of selected cores from underneath the upwelling gyre at 5°N, where the oxygen minimum zone intersects the slope and from the deep southern Somali basin, indicate that the lack of organic matter in settings favourable to organic carbon storage may be due to the nature of the organic matter, and that periods of intensified upwelling may leave no geochemical imprint in the sediment.

During the NIOP C1 and C2 cruises, box- and piston-core samples were collected at three transects, one transect off Somalia and the others off SW Oman and Yemen (van Hinte *et al.*, 1995), in the OMZ of the eastern Arabian Sea, and of the Indus Fan (van der Linden and van der Weyden, 1994). The transects off Oman and Yemen covered stations in 74–2215 m water depth, occupied in both the upwelling and the non-upwelling season. Sediments are predominantly green organich-rich calcareous sediments. Down to a water depth of at least 770 m they contain a large fraction of biogenic, fine sand and wind blown quartz. Below 770 m the sand fraction is negligible and calcareous silty clays predominate. All cores have been extensively burrowed and contain variable amounts of organic carbon (see below). Shell fragments are common to abundant in sediments from between 1118 and 75 m depth, and appear to be redeposited.

The Somali transect cores show that the upper slope stations contain an undisturbed, relatively high sedimentation area underlying the upwelling gyre at 10°N (stations down to 905, Fig. 5), but the downslope and basin cores 907, 908 and 915 contain numerous turbidite intervals, similar to those observed by Caulet *et al.* (1987). These observations fit with the interpretation of a single channel seismic profile we collected along the sampling transect, which shows that large scale slumping and sliding has affected the middle and lower Somali continental slope. Mass wasting deposits derived from the lower slope extend far into the Somali Basin and may well develop into turbidite deposition in the deeper part of the Somali Basin.

Off Oman and Yemen only 3.5 kC profiles were recorded. These show irregular seabed topography with sediments at the surface, frequently disturbed by small-scale slumping, especially between 1000 and 1500 m water depth.

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