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**Plymouth Marine Laboratory
Cruise Report**

**Nutrient and Trace Metal Biogeochemical
Cycling in the N W Indian Ocean**

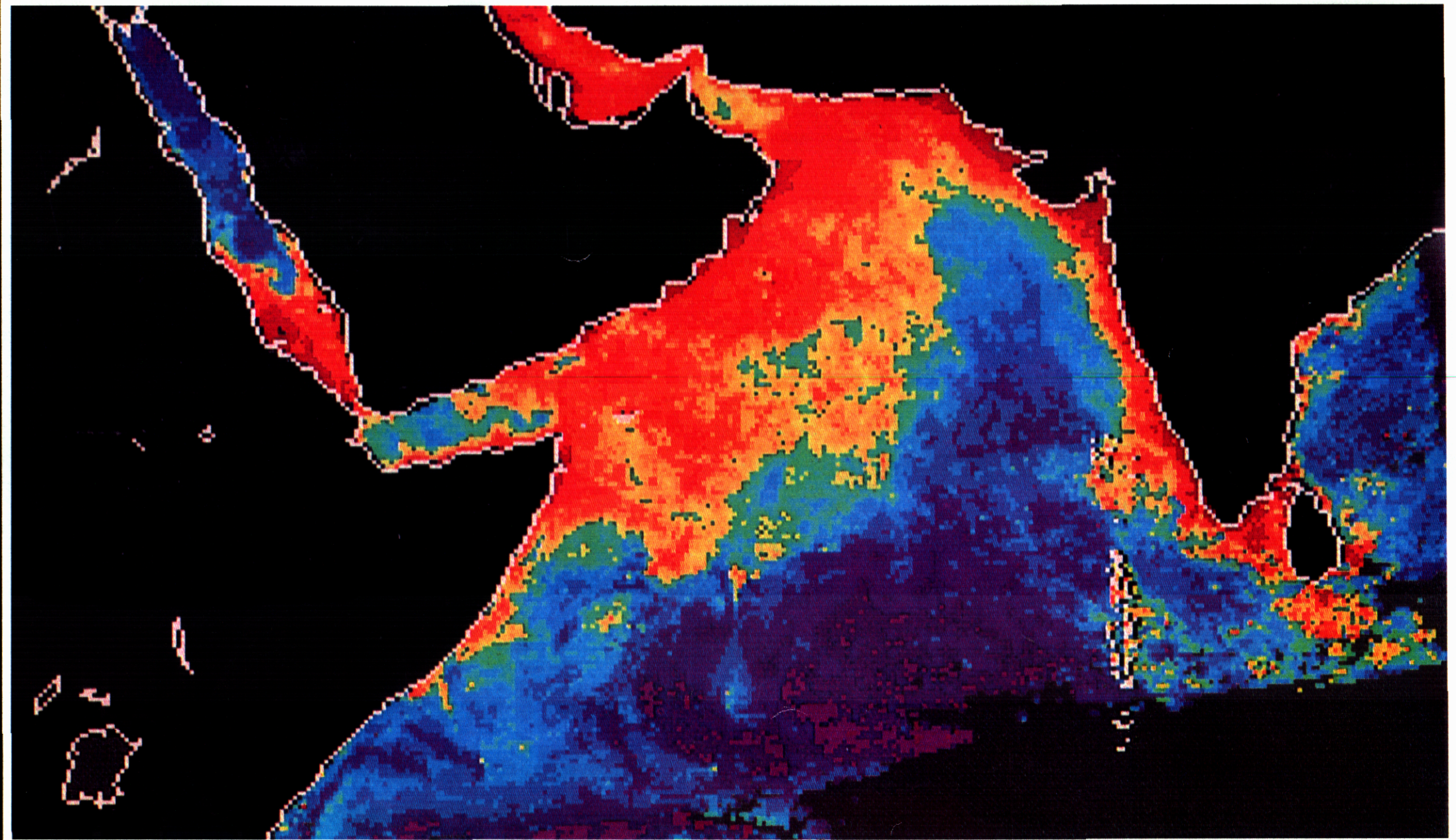
**R R S Charles Darwin
Cruise CD 16/86: 8 September 12 October 1986**

**Principal Scientist
Dr R F C Mantoura**

August 1991

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1. INTRODUCTION

The North West Indian Ocean (NWIO, Figure 1) encompasses some of the biogeochemically most extreme conditions found in any ocean, ranging from the oligotrophic subtropical gyre (Figure 4f), to an underlying hypoxic intermediate (100 - 1200 m) water mass (Figure 4 b) extending southward from the Arabian Sea to 12°N, to a pronounced seasonal upwelling regime off coastal Somalia and SE Arabian Peninsular driven by the S W Monsoons. Our biogeochemical studies have focussed on assessing the contrasting vertical profiles and fluxes of carbon, nitrogen and trace metals in relation to the oceanographic water masses that characterise the different regions of the NWIO. Scientists from the UK, Germany, USA and Holland (see Section 2) participated in this most stimulating and successful cruise which to date has resulted in over 9 important publications summarised at the end of the Report. I must thank the Natural Environment Research Council in supporting this cruise and to acknowledge their patience in awaiting this technical Cruise Report even though the supporting data have been widely available and exchanged with scientific community. We here also acknowledge the professional and efficient support provided by the Captain, Officers, crew of the R R S Charles Darwin, and the technical support personnel of the NERC Research Vessel Services.

What were the main discoveries?

The surface concentration of NO_3 as measured by sensitive chemiluminescence techniques were found to be severely depleted to nanomolar levels (Mantoura et al 1992, Figure 4f) in the subtropical gyre increasing by over a thousand times within the upwelling waters off Oman. These surface NO_3 levels exerted a major control on 'New' Production as measured by the $^{15}\text{NO}_3$ assimilation techniques (Owens et al 1992) carried out in *in situ* incubation systems. Phytoplankton production (Table 3) in the oligotrophic waters was low ($<0.3 \text{ gC m}^{-2} \text{ d}^{-1}$) and dominated by $<0.8 \mu\text{m}$ picoplanktonic cyanobacteria (Figure 7) whose biomass contributed significantly to the particulated organic carbon (Burkill et al 1992). Bloom production conditions of $>2.6 \text{ gC m}^{-2} \text{ d}^{-1}$ occurred in upwelling waters which were dominated by large ($>5 \mu\text{m}$) diatoms. The vertical flux of sedimenting POC (Zeitzschell, 1992; Table 2) to the deep sea correlated with upwelling production, and this was ultimately responsible for maintaining the suboxic conditions in the intermediate waters of NWIO. Bacterial abundance and production (Ducklow, 1992; Figure 6) estimated using uptake of tritiated thymidine were high relative to primary production, and this required a significant flux of dissolved organic carbon from sinking particle flux to support this bacterial production.

Throughout the NWIO, we found extensive evidence for denitrification of NO_3 to yield volatile N_2O (Law and Owens, 1990), a potent greenhouse gas, and a NO_3 deficit (Mantoura et al 1992) within the oxygen-depleted intermediate waters. We calculated that the N_2O ventilation fluxes from the NWIO could account for up to 10% of the global ocean denitrification to the atmosphere. Likewise, supersaturated levels of methane, another greenhouse gas, were found (Owens et al 1991) to derive from sedimenting phyto-genic organics just below the chlorophyll maximum, and its

ventilation in the upwelling regions could contribute a major proportion of the global marine flux of methane to the atmosphere.

The concentrations of dissolved rare earth elements (REE's, German and Elderfield, 1990) and transition elements (Fe, Mn, Cu, Cd, Zn, Ni, Saager et al 1989) were profiled reliably for the first time in the Indian Ocean to reveal levels which were intermediate between Atlantic and Pacific Oceans, consistent with general ocean circulation and deep regeneration process. Metals (Ce, Mn, Fe) scavenged onto settling particles from the oxygenated surface zone were observed to be regenerated in the suboxic zones of NWIO. Other metals (Cd, Zn, Ni & Cu) exhibited nutrient like behaviour involving biological removal in surface productive waters and oxidative regeneration at depth. A paper on the aluminium distribution in relation to atmospheric and continental inputs to the Indian Ocean is near completion (Howland and Mantoura, 1991 in prep).

Detail summaries of all the above findings can be found in the appended list of Abstracts at the end of this Cruise Report.

Certainly it can be said that this Indian Ocean Expedition was the first attempt by chemists and biologist at Plymouth to mount an ocean-scale biogeochemical study that has served as prototype to subsequent studies such as BOFS. Since there are plans to return to the NWIO within the PRIME successor project to BOFS, this Cruise Report is very timely.

R F C Mantoura Plymouth Marine Laboratory, August 1991.

2. PERSONNEL

2.1 Scientific Staff

R Fauzi C Mantoura	Plymouth Marine Laboratory ¹
Nicholas J P Owens	Plymouth Marine Laboratory ¹
Peter H Burkill	Plymouth Marine Laboratory ¹
Bernt Zeitzschel	Institute fur Meereskunde, Kiel ²
Hugh Ducklow	University of Maryland, USA ³
Hein deBaar	Netherland Institute of Sea Research ⁴
Robin J Howland	Plymouth Marine Laboratory ¹
Dave Conway	Plymouth Marine Laboratory ¹
Malcolm S-Woodward	Plymouth Marine Laboratory ¹
Jenne Morris	Plymouth Marine Laboratory ¹
Cliff Law	PML & Univ of Dundee
Carole Llewellyn	Plymouth Marine Laboratory ¹
Ray Leakey	PML & Univ of Southampton
Ian Bellam	Plymouth Marine Laboratory ¹

2.2 Ship's Staff

G Long	Master, Research Vessel Base ⁵
K Avery	Chief Officer, RVS ⁵
P Evans	2nd Officer RVS ⁵
A Maltby	3rd Officer RVS ⁵
J Baker	Radio Officer RVS ⁵
R Hagger	Chief Engineer RVS ⁵
A Adams	2nd Engineer RVS ⁵
B Macdonald	3rd Engineer RVS ⁵
P Parker	Electrical Engineer RVS ⁵
G Pook	Bosun RVS ⁵
A Roach	Seaman RVS ⁵
A Olds	Seaman RVS ⁵
B Craddock	Seaman RVS ⁵
D Bevan	Seaman RVS ⁵
C Sluman	Seaman RVS ⁵
P Harris	Cook Steward RVS ⁵
S Rogers	Ships Cook RVS ⁵
J Orsborn	2nd Steward RVS ⁵
W Young	Steward RVS ⁵
C Kelley	Steward RVS ⁵
M Williams	Motorman RVS ⁵

C Paulson
A Robinson
N Herbert
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3 BACKGROUND AND OBJECTIVES

3.1 SCIENTIFIC BACKGROUND TO THE INDIAN OCEAN EXPEDITION

The chemical forms of nitrogen and their microbiological transformation exert a major control on oceanic productivity and biogeochemistry. Our previous studies into nitrogen cycling have concentrated on UK estuaries, embayments and shelf waters, which are relatively rich in nitrogen (NO_3^- , NO_2^- , NH_4^+ $> 1.0 \mu\text{M} - \text{NI}^{-1}$). We propose to extend these studies into the contrasting environments of the oligotrophic ($0.01 - 0.50 \mu\text{M} - \text{NI}^{-1}$) and deoxygenated waters of the Indian Ocean.

The dynamics and mechanisms of nitrogen cycling in oligotrophic waters are tightly coupled between consumers (phytoplankton) and recyclers (bacteria, microzooplankton). But oligotrophic levels of nutrients have usually escaped detection and so the cycles are poorly understood. The North West Indian Ocean (NWIO; 02-20N, 50-70E, see Fig. 1) is characterized, as in other Ocean systems, by a large oligotrophic gyre but, unlike other ocean systems, includes seasonal upwelling of nutrient-rich bottom water along the Somali and SE Arabian coastline during the SW monsoons (April-September). The resultant off-shore gradients in nutrients (eg PO_4 gradient: $3 \rightarrow 0.15 \mu\text{M} - \text{P L}^{-1}$) and primary production ($> 1000 \text{ mg C m}^{-2} \text{ day}^{-1} \rightarrow < 50 \text{ mg C m}^{-2} \text{ day}^{-1}$) are prominent over relatively short distances (~ 400 nautical miles).

Another unique feature of the NWIO is the presence of an oxygen depleted zone (ODZ; $\text{O}_2 < 0.1\%$ saturation) at 200 - 2000 m depth below the whole Indian Ocean. The ODZ is particularly pronounced in the Arabian Sea (Fig. 2). Within the ODZ, nitrogen regeneration pathways switch from oxidative mechanisms (eg nitrification) to reductive mechanisms in which NO_3^- replaces O_2 as terminal electron acceptor for the microbial oxidation of organic matter. The ODZ of the NWIO is one of only three permanent denitrifying environments (Eastern Tropical North Pacific and Coastal Peru), in which NO_3^- is bacterially reduced to N_2 , thus comprising a major route for returning N_2 to the atmosphere.

We propose to use novel sensitive analytical and microbiological techniques together with sedimentation traps to investigate the sources, fluxes and transformation of nitrogen in upwelling, oligotrophic and O_2 -depleted zones of the NWIO.

3.2 SPECIFIC OBJECTIVES

1 - To determine the vertical distribution and hydrochemistry of nitrogen compounds (NO_3^- , NO_2^- , N_2O , NH_4^+ , urea R-NH_2 , oxygen and particulate nitrogen (detrital, phytoplankton pigments) along off-shore sections of 11 stations from Gulf of Oman in SE Arabia to the Central oligotrophic gyre (05N, 67E) and equatorial waters.

2 - To quantify the rates of nitrogen assimilation by size-fractionated phytoplankton in relation to their ecophysiology (Nitrogen preference, kinetics, light dependence).

3 - To estimate bacterial and microzooplanktonic recycling of nitrogen using ^{15}N isotope dilution techniques, grazing dilution and precision respirometry, in euphotic and oxygen-depleted zones (ODZ) of the NWIO. Stations shown in Table 1 will be measured by *in situ* or shipboard incubations using (a) ^{15}N for phytoplankton assimilation of NO_3^- , NO_2^- , NH_4^- and N_2 fixation, and microheterotrophic regeneration of NH_4^- ; (b) ^{14}C phytoplankton production; (c) precision O_2 respiration and photosynthetic production in response to N enrichment; (d) N_2 fixation estimates by C_2H_2 reduction.

3 - The net transformation rates of nitrogen in euphotic waters will be followed over the short term (two days) using ^{15}N 'pulse chase' experiments and trace nutrients analyses.

4 - Nutrients, salinity, temperature, O_2 , *in vivo* fluorescence, and near surface vertical variability of chlorophyll, S, T will be continuously monitored between stations and in the upwelling waters off SE Arabia.

5 - Free drifting triple sedimentation trap array will be deployed over periods of 1 - 25 days to quantitate sedimentation, losses from the euphotic chemocline and suboxic aphotic regions of the water column.

6- to investigate bacterial abundance and productivity within the productive, oxygen depleted and upwelling waters of the NWIO.

7- To determine the vertical and latitudinal distribution of trace metals and rare earth elements in the NWIO.

4 SCIENTIFIC RECORD

- Cruise track and stations are shown in Figure 1.
- The deployment and recovery dates and times, position, station numbers and associated oceanographic data for CTD, sediment traps, incubation rig and UOR deployments are listed in Tables, 1, 2, 3 and 4 respectively. Excell Spreadsheets of the CTD data, O₂ fluorescence, nutrients (NO₃, NO₂, PO₄, Si, NH₃), pigments and N₂O, are available from Dr R F C Mantoura.

Monday, 8 September, Day 251 (All times recorded in GMT, n.b. local time = GMT + 4 hours).

Completion of staff O/B, equipment checklist and commissioning.

1600 Depart Victoria (Seychelles) for Shakedown station (03 00'S, 57 44'E).

Tuesday 9 September, Day 252

- 0226 CTD shallow (0-300 m) Shakedown cast #0101; I/B: 0338 .
- 0530 CTD deep (1-1500 m) Shakedown #0201 I/B 0745.
- 0922 Trial deployment of sediment trap I/B 1128
- 1535 Commence UOR tow # CD 98601 en route to Victoria I/B 1733
Steam to Victoria for pick up of radiochemical airfreight consignment for Dr Ducklow.

Wednesday 10 September, Day 253

- 1045 Victoria Harbour: Pick up scientific package for Dr Ducklow. Proceed to Station 01 (Revised St 01 destination (00 00'N, 65 00'E).

Thursday 11 September, Day 254

- 0510 Launch UOR tow # CD 98602 tow at 10 kts I/B 0824
- 0945 Launch UOR tow # CD 98603 tow at 10 kts I/B 1255.

Friday 12 September, Day 255

In passage to St 01.

Saturday 13 September, Day 256

- 0022 Arrive St 01 (00 00.0'N, 65 00'E).
- 0028 CTD cast 0101. Pre dawn primary production cast. Go Flo bottles pairs fired at 69, 55, 42, 28, 14 and 1 m depth. I/B 0131.

- 0327 Deploy ^{14}C , ^{15}N , O_2 incubation rig # 1.
- 0506 Deploy sediment trap (100 m) rig # 1 tethered to primary production rig.
- 0536 CTD surface water sampling for NH_3 analyser. I/B 1610.
- 0635 CTD biogeochemical deep cast # 0103. (Depths 700, 800, 900, 1000, 1100, 1200, 1500, 2000, 2600, 3000, 3500, 3900). I/B 1053.
Water sample splits for "Biogeochemical Casts" for, nutrients, O_2 , CH_4 , N_2O bacterial counts, particle sizing, pigments and trace metal analyses carried out on all 'chemical' casts (Table 1) are shown in Figure 2.
- 1114 Vertical profile with UOR package.
- 1426 Production rig #1 I/B.
- 1453 CTD biogeochemical cast # 0104 (depths: 4, 34, 54, 70, 90, 129, 168, 268, 351, 397, 500, 600 m). I/B 1606.
- 1900 CTD profiling cast 0105 (0-200) I/B 1917 (no samples).

Sunday 14 September, Day 257

- 0015 CTD production cast # 0106. Bottle pairs at 69, 55, 42, 28, 14, 1 m depth. I/B 0103.
- 0230 Deploy ^{14}C , ^{15}N O_2 production rig # 2.
- 0618 CTD and bottles fired at 51 m (cast # 0107).
- 1232 CTD cast # 0108 REE samples (70 m) I/B 1314.
- 1350 Production rig # 2 I/B.
- 1830 CTD cast # 0109 profiling I/B 1900.
- 1930 LHPR oblique tow at 3.5 kt. I/B 2058.

Monday 15 September, Day 258

- 0222 CTD cast # 0110 for ^{15}N , pigments (1-1200 m). I/B 0418.
- 0506 Recovery of sediment trap #1.
- 0630 Depart St 1 toward St 2.
- 0718 Deploy UOR two # 98604, recover 1312.
- 1352 Deploy UOR tow # 98605, recover 0516 16.9.91

Tuesday 16 September, Day 2559

- 0548 Arrive St 2 (04 00.0'N, 67 00.0'E).
- 0618 CTD shallow biogeochemical cast # 0201 (depths: 0, 20, 40, 60, 80, 100, 150, 200, 300, 400, 500, 600 m). I/B 0822.
- 1002 CTD deep biogeochemical cast # 0202 (depths: 0, 700, 800, 900, 1000, 1250, 1500, 1750, 2500, 3000 m). I/B 1346.
- 1514 LHPR streamed. I/B 1635.
- 1642 Depart St 2 proceed to St 3.
- 1643 Deploy UOR two # 98606. Recover 0448 17.9.91.

Wednesday 17 September, Day 260

- 0000 In passage St 2 to St 3.

- 0750 Deploy UOR tow # 98607. I/B 1624.
1642 Arrive St 3 (08 00N, 67 00'E).
1715 Postponed sediment trap deployment. Capstan failure.

Thursday 18 September, Day 261

- 0023 CTD production cast # 0301. Paired bottles fired at 100, 80, 60, 40, 20, 0 m. I/B 0054.
0231 Production rig # 3 O/B.
0323 CTD Deep biogeochemical cast # 0302 (depths 10, 616, 700, 880, 960, 1100, 1199, 1400, 2000, 2750, 3500, 4663) I/B 0848.
0940 UOR light profile I/B 0959.
1048 CTD shallow biogeochemical cast # 0303 (depths 15, 57, 71, 87, 105, 125, 145, 195, 293, 392, 491) I/B 1254.
1333 Production rig # 3 I/B.
1556 Deploy sediment trap # 2 at. Twin poisoned/unpoisoned pairs.

Friday 19 September, Day 262

- 0024 CTD production cast # 0304. Paired bottles at 100, 80, 60, 40, 20 m depth. I/B 0105.
0217 Production rig #4. O/B.
0911 Trial UOR deployment I/B 0955.
1015 CTD cast # 0305. microzooplankton grazing.
1439 Recover sediment trap rig #2.
1640 LHPR tows. I/B 1824.
1842 Deploy UOR tow # 98608.
1845 Depart St 03 proceed to St 04.

Saturday 20 September, Day 263

- 1918 Arrive St 4. (12 00.0'N, 67 00.0'E).
2051 CTD deep biogeochemical cast 0401 (depths 5, 600, 700, 800, 1000, 1500, 1750, 2250, 2750, 3500, 4250 m). I/B 0112 21.9.86.

Sunday 21 September, Day 264

- 0237 CTD primary production deck incubation cast. I/B 0248 (10 m, 6 bottles).
0327 CTD shallow biogeochemical cast # 0402 (depths 0, 20, 40, 60, 80, 100, 150, 250, 300, 400, 500, 1000 m). I/B 0536.
0648 LHPR oblique tow. I/B 0900.
0907 Depart St 04 proceed to St 05.
0908 Deploy UOR two # 98609. I/B 2309.

Monday 22 September, Day 265

- 0010 Arrive St 05. (14 25.7'N, 66 56.2'E).
0012 CTD production predawn cast # 0501 (paired bottles fired at 100, 60, 45, 30, 15, 0 m). I/B 0018.

- 0134 Deploy twin (poisoned/unpoisoned) sediment traps at 100 m # 3.
- 0216 Deploy ¹⁴C, ¹⁵N, O₂.
- 0313 CTD deep biogeochemical cast # 0502 (depths 20, 600, 700, 900, 1000, 1250, 2000, 2500, 3000, 4000 m). I/B 0736.
- 0910 Deployed second sediment trap (500 m) unpoisoned. # 4.
- 1029 CTD shallow biogeochemical cast # 0503 (depths 4, 40, 60, 80, 100, 125, 150, 175, 200, 300, 400, 500 m). I/B 1206.
- 1328 Recovery production rig #5.

Tuesday 23 September, Day 266

- 0016 CTD production cast 0504. Paired bottles fired at 2, 13, 28, 47, 50, 75 m). I/B 0046.
- 0128 Deployed ¹⁴C, ¹⁵N, AO₂ primary production rig #6.
- 0303 CTD cast 0505. (0-200 m) microzooplankton grazing, bacterial production experiments. I/B 0356.
- 0500 CTD High resolution biogeochemical cast # 0506 (100-300 m). I/B 0636.
- 0800 Secchi, plankton, haul, UOR sensor haul.
- 0932 CTD high resolution biogeochemical cast #0507 (60-400 m). I/B 1039.
- 1145 CTD high resolution biogeochemical cast # 0508 (0-400 m). I/B 1323.
- 1340 Recover production rig #6. I/B 1403.
- 1534 Recover sediment trap #3. I/B 1511.
- 1550 Recover sediment trap #4. I/B 1634.
- 1766 LHPR oblique tow at 3.5 kts. I/B 1854.
- 1900 Depart St 05 proceed St 06.
- 1910 Deploy UOR two # 98610A not undulating, therefore aborted 1955.
- 2027 Deploy UOR tow # 98610. Passage to St 06.

Wednesday 24 September, Day 267.

In passage St 05 to 06.

- 1529 Recover UOR tow # 98610.
- 2241 Arrive Station 06. (19 00'N, 67 00'E).

Thursday 25 September, Day 268

- 0236 CTD deep biogeochemical cast # 0601 (depths 5, 300, 400, 500, 800, 1000, 1200, 1600, 2500, 3200 m). I/B 0625.
- 0924 CTD shallow biogeochemical cast # 0602 (depth 5, 10, 20, 40, 50, 70, 90, 120, 150, 175, 200 m). I/B 1022.
- 1125 LHPR oblique haul I/B 1258.
- 1300 Depart St 06 proceed St 07.
- 1321 Deploy UOR tow # 98611.

Friday 26 September, Day 269

- 1141 UOR two # 48611 I/B. Proceed full speed St 07.
- 1330 Arrive St 07. (21 15.1'N, 60 15'E).
- 1350 CTD profiling/microzooplankton cast # 0701 (0-100 m). I/B 1454.

- 1534 CTD ¹⁵N/denitrification cast # 0702 (0-400 m). I/B 1642.
- 1720 Deploy 50 m twin sediment traps #5.
- 1820 Deploy 500 single sediment trap #6.

Saturday 27 September, Day 270

- 0015 CTD production cast #0703. Twin bottles fired out 7, 14, 21, 27, 35 m. I/B 6048.
- 0144 Deploy ¹⁴C, ¹⁵N, AO₂ primary production rig #7.
- 0240 CTD deep biogeochemical cast # 0704 (depths, 175, 200, 285, 400, 600, 800, 1000, 1200, 1600, 2000, 2500, 3360 m). I/B 0645.
- 0715 LHPR oblique tow. I/B 0845.
- 1023 CTD shallow biogeochemical cast # 0705 (depths 4, 10, 20, 40, 50, 60, 80, 100, 125, 150, 175 m). I/B 1130.
- 1320 Recover production rig #7 I/B 1342.
- 1431 Recover sediment trap #5 (50 m). I/B 1500.
- 1531 Recover sediment trap #6 (500 m). I/B 1551, 1610.
- 1645 LHPR oblique tow I/B 1800.
- 1806 Depart St 07 proceed St 08.
- 1808 UOR tow #98612. Passage to St 08. I/B 1039 28.9.86.

Sunday 28 September, Day 271

- 1130 Arrive St 08 (22 40.4'N, 60 40.6'E).
- 1134 CTD deep biogeochemical cast # 0801 (depths 175, 200, 240, 400, 600, 800, 1000, 1200, 1600, 2000, 2500, 3000 m) I/B 1543.
- 1745 CTD shallow biogeochemical cast # 0802 (depths 3, 5, 10, 15, 20, 39, 50, 75, 100, 125, 150, 200 m). I/B 1900.
- 1920 Depart St 08 proceed St 10 (bypass 09).
- 1929 UOR tow #98613. Recover 1053 29.9.86.

Monday 29 September, Day 272

Passage St 08 to St 10.

- 1100 Arrive St 10 (24 20.4'N, 58 09.7'E).
- 1115 CTD deep biogeochemical cast # 1001 (depths 150, 180, 200, 301, 400, 600, 800, 1000, 1200, 1600, 2000, 2633 m). I/B 1453.
- 1632 CTD shallow biogeochemical cast #1002 (depths 3, 10, 20, 39, 40, 45, 50, 60, 80, 100, 125 m). I/B 1630.

Tuesday 30 September, Day 273

- 0203 CTD chlorophyll cast 0-50 m 6 bottles fired. I/B 0227.
- 0230 Depart St 10 proceed St 11.
UOR tow # 98614. I/B 0748.
- 0800 Arrive St 11 (24 49'N, 57 13.0'E).
- 0808 CTD deep biogeochemical cast #1101 (depths 60, 75, 100, 140, 200, 240, 300, 350, 400, 600, 800, 1218 m). I/B 1016.

- 1124 CTD neodymium cast #1102. (6 bottles at 240 m. 6 bottles at 75 m). I/B 1204.
- 1232 CTD shallow biogeochemical cast #1103 (depths 0, 10, 15, 20, 25, 30, 35, 38, 40, 45, 50, 55, M). I/B 1338.
- 1435 depart St 11, proceed to 09 (bypass St 10). UOR tow # 98615. I/B 0245 (1.10.96).

Wednesday 1 October, Day 274

- 0250 Arrive St 09 (23 40.11'N, 59 04.75'E).
- 0304 CTD ¹⁵N, denitrification cast 0901 (0-500 m). I/B 0438.
- 0500 Deploy sediment trap (Twin, 50 m) #7. O/B 0520.
- 0535 Deploy sediment trap (500 m) #8. O/B 0610.
- 0835 CTD Trace element cast 0902 (6 bottles at 500, 226 m depth). I/B 0937.
- 0952 Vertical light sensor (UOR).
- 1100 LHPR oblique haul. I/B 1220.
- 1236 CTD shallow biogeochemical cast 0903 (depths 5, 10, 25, 35, 45, 60, 75, 100, 200, 300, 400, 500 m). I/B 1348.

Thursday 2 October, Day 275

- 0011 CTD production cast 0904 (twin bottles fired at 10, 20, 30, 40, 50 m). I/B 0048.
- 0144 Deploy ¹⁴C, ¹⁵N, AO₂ primary production rig #8/ O/B 0211.
- 0232 CTD deep biogeochemical cast # 0905 (depths 170, 200, 300, 400, 600, 800, 100, 1200, 1600, 2000, 2300, 2151 m). I/B 0600.
- 0620 UOR vertical profiles. I/B 0640.
- 0936 CTD shallow biogeochemical cast #0906 (depths 5, 10, 15, 20, 25, 30, 35, 40, 60, 90, 120, 140 m). I/B 1100.
- 1154 Recovery sediment trap #8. I/B 1250.
- 1344 Recovery production rig #8. I/B 1355.
- 1454 Recovery sediment trap #7. I/B 1500.
- 1521 CTD microzooplankton cast # 0907. I/B 1557.
- 1606 Depart St 09 proceed to St 13 (bypass 12).
- 1608 Deploy UOR two # 98616.
- 1625 UOR towing cable snapped. UOR confirmed lost (23 34.5'N, 59 06.0'E, DR).

Friday 3 October, Day 276

- Passage St 09 to St 13.
- 1444 Arrive St 13 (19 59.6'N, 60 44.7'E).
- 1456 CTD deep biogeochemical cast #1301 (depth, 6, 400, 600, 800, 1000, 1200, 1400, 1600, 2000, 2500, 3000, 3500 m). I/B 1900.
- 1958 CTD shallow biogeochemical cast # 1302 (depths 10, 20, 30, 40, 50, 60, 80, 100, 120, 150, 190, 300 m). I/B 2123.
- 2130 Depart St 13, proceed St 14.

Saturday 4 October, Day 277

- 1040 Arrive St 14 (17 24.9'N, 61 20.1'E).
- 1116 CTD ¹⁵N cast #1401 (0-500 m). I/B 1224.
- 1250 Deploy shallow (75 m) twin sediment traps #9. O/B 1307.
- 1357 Deploy deep (500 m) sediment trap #10. O/B 1430.
- 1437 LHPR oblique haul. I/B 1610.

Sunday 5 October, Day 278

- 0001 CTD production cast # 1402 (twin bottles fired at 0, 10, 20, 30, 40, 50 m). I/B 0041.
- 0130 Deployed ¹⁴C, ¹⁵N O₂ primary production rig #9. O/B 0155.
- 0222 CTD deep biogeochemical cast # 1403 (depths 45, 600, 889, 1000, 1200, 1400, 1600, 2000, 2500, 3000, 3500, 3868 m). I/B 0756.
- 1010 CTD microzooplankton cast # 1404 (95 m 21 m). I/B 1054.
- 1130 CTD shallow biogeochemical cast # 1405 (depths 17, 40, 60,80, 100, 125, 150, 175, 199, 250, 300, 400 m). I/B 1308.
- 1340 Recovery production rig #9. I/B 1355.
- 1448 Recovery shallow sediment trap #9. I/B 1507.
- 1005 Recovery of dep sediment trap #10. I/B 1612.
- 1642 Depart St 14 proceed to St 15.

Monday 6 October, Day 279

- 0245 Arrive St 15 (18 15.0'N, 59 45.0'E).
- 0302 CTD Deep biogeochemical cast 1501 (depths 6, 400, 600, 800, 1000, 1200, 1400, 1600, 2000, 2500, 3000, 3650 m). I/B 0725.
- 0914 CTD shallow biogeochemical cast 1502 (depths 5, 8, 16, 24, 40, 50, 70, 110, 120, 150, 200, 300 m). I/B 1045.
- 1107 LHPR oblique tow. I/B 1223.
- 1230 Depart St 15, proceed St 16.
- 2311 Arrive St 16 (19 27.1'N, 58 18.7'E).

Tuesday 7 October, Day 280

- 0005 CTD Production cast # 1601 (twin bottles fired at 5, 8, 15, 24, 32, 40 m). I/B 0034.
- 0120 Deploy ¹⁴C, ¹⁵N, O₂ primary production rig #10. O/B 0136.
- 0205 Deploy shallow (50 m) twin sediment traps #11. O/B 0220.
- 0225 Deploy second shallow multisampler sediment trap. O/B 0254.
- 0507 CTD shallow biogeochemical cast #1602 (depths 10, 20, 40, 60, 80, 129, 250, 350, 450, 585 m). I/B 0650.
- 0933 CTD microzooplankton cast #1003. (5,50 m). I/B 1044.
- 1330 Recovery production rig #10. I/B 1340.
- 1440 LHPR oblique tow. I/B 1605.

Wednesday 8 October, Day 281

- 0455 Recovery twin sediment traps #11. I/B 0506.

0904 CTD ¹⁵N cast #1604 (0-450 m). I/B 1016.
1400 Recovery automatic sediment trap #12. I/B 1410.
1700 Scientific operation complete. Passage to Qaboos. Complete outstanding
analyses on board in passage to Qaboos.

Circulation list

DR N J P Owens
Dr P H Burkill + 1 (Dr R Leakey)
Dr C Law
Mr M Woodward
Dr M Whitfield
Mr R Howland
Mr D Conway
Ms C Llewellyn
Mr I Bellan
Dr S White
Dr D Fay
Dr Hein de Baar
Dr P Herring
Dr H Ducklow
Prof B Zeitzschel
Prof P J Le B Williams

Table 1

Listing of CTD Stations, positions, hydrocast numbers, depths and cast types.

ST	CAST	DATE	TIME GMT	DEPTH RANGE	*	LAT	LONG
Sh' down							
	S0101	9.9.86	0226	0-300	C	03 01.4S	57 44.7E
	S0102	9.9.86	0530	1-1500	C	03 02.8S	57 45.1E
1	0101	13.9.86	0028	0-70	R	00 00.15N	65 00.3E
	0102	13.9.86			E	00 02.3N	65 00.0E
	0103	13.9.86	0640	700-3900	C	00 02.4N	64 59.9E
	0104	13.9.86	1453	0-600	C	00 03.7N	65 05.6E
	0105	13.9.86	1902	0-200	P	00 04.2N	65 05.9E
	0106	14.9.86	0015	0-200	R	00 07.5N	65 07.4E
	0107	14.9.86	0618	50	E	00 07.2N	65 12.1E
	0108	14.9.86	1232	70	E	00 10.7N	65 14.3E
	0109	14.9.86	1833	200	E	00 12.4N	65 19.8E
	0110	15.9.86	0222	0-1200	C	00 13.8N	65 22.6E
2	0201	16.9.86	0630	0-600	C	03 59.6N	67 00.1E
	0202	16.9.86	1005	0-3100	C	03 59.3N	67 00.8E
3	0301	18.9.86	0023	0-200	R	07 59.9N	66 59.7E
	0302	18.9.86	0323	600-4500	C	08 00.8N	66 59.1E
	0303	18.9.86	1048	0-500	C	07 59.6N	67 00.4E
	0304	19.9.86	0031	0-100	R	07 57.2N	67 00.6E
	0305	19.9.86	1030	0-1000	E	07 55.8N	67 01.4E
4	0401	20.9.86	2038	600-4200	C	11 59.8N	66 58.8E
	0402	21.9.86	0327	0-500	C	11 59.6N	66 58.9E
5	0501	22.9.86		0-75	R	14 25.6N	66 55.4E
	0502	22.9.86	0313	0-3900	C	14 25.6N	66 55.3E
	0503	22.9.86	1029	0-500	C	14 22.4N	66 54.2E
	0504	23.9.86		0-75	R	14 22.5N	66 54.0E
	0505	23.9.86	0308	0-200	E	14 22.3N	66 51.4E
	0506	23.9.86	0500	100-300	C	14 21.6N	66 50.6E
	0507	23.9.86	0921	60-400	C	14 20.3N	66 54.5E
	0508	23.9.86	1145	0-400	C	14 18.3N	66 56.1E
6	0601	25.9.86	0236	0-3200	C	18 59.9N	67 00.5E
	0602	25.9.86	0940	0-200	C	18 58.6N	66 59.5E
7	0701	26.9.86	1350	0-100	E	21 15.1N	63 15.1E
	0702	26.9.86	1535	0-400	E	21 14.8N	63 15.7E
	0703	27.9.86	0016	0-35	R	21 16.1N	63 18.7E
	0704	27.9.86	0240	175-3300	C	21 15.5N	63 21.9E
	0705	27.9.86	1023	0-175	C	21 14.1N	63 27.1E
8	0801	28.9.86	1134	175-3000	C	22 39.6N	60 40.6E
	0802	28.9.86	1734	0-200	C	22 39.3N	60 42.4E
9	0901	1.10.86	0304	0-500	E	23 40.1N	59 04.8E
	0902	1.10.86	0837	230-500	E	23 40.0N	59 04.2E
	0903	1.10.86		0-500	C	23 39.1N	59 05.7E

	0904	2.10.86	0015	0-50	R	23	40.5N	59	03.4E
	0905	2.10.86	0232	175-2750	C	23	38.1N	59	01.4E
	0906	2.10.86	0936	0-140	C	23	35.4N	59	00.0E
	0907	2.10.86	1522	0-3	E	23	36.0N	58	59.9E
10	1001	29.9.86	1121	150-2700	C	24	20.5N	58	09.7E
	1002	29.9.86	1632	0-200	C	24	18.16N	58	10 E
	1003	30.9.86	0203	0-50	E	24	19.9N	58	09.8E
11	1101	30.9.86	0808	60-1200	C	24	49.3N	57	12.8E
	1102	30.9.86	1126	75-240	E	24	49.1N	57	13.3E
	1103	30.9.86	1232	0-55	C	24	49.5N	57	12.9E
13	1301	3.10.86	1458	0-3500	C	19	58.0N	60	47.7E
	1302	3.10.86	2000	0-300	C	19	58.1N	60	48.9E
14	1401	4.10.86	1116	0-500	C	17	24.6N	61	20.5E
	1402	5.10.86	0001	0-50	R	17	26.5N	61	30.6E
	1403	5.10.86	0222	0-3500	C	17	25.6N	61	29.1E
	1404	5.10.86	1010	0-100	E	17	26.3N	61	34.1E
	1405	5.10.86	1130	0-400	C	17	26.2N	61	35.3E
15	1501	6.10.86	0304	0-4000	C	18	12.2N	59	42.2E
	1502	6.10.86	0914	0-300	C	18	13.2N	59	44.3E
16	1601	7.10.86	0005	0-40	R	19	27.1N	58	18.8E
	1602	7.10.86	0507	0-580	C	19	24.1N	58	18.1E
	1603	7.10.86	0933	0-43	E	19	26.7N	58	18.7E
	1604	8.10.86	0904	0-450	E	19	26.7N	58	18.7E

* C - Chemical cast
R - Production
E - Experiments
P - Profiling

Table 2

Sediment Trap Deployment and Flux data.

Station No.	Depth m	Date 1986	Exposure h	Drift nm	Speed kn	unp. pois.	Seston $\text{mg m}^{-2}\text{d}^{-1}$	Carbon $\text{mg m}^{-2}\text{d}^{-1}$	Nitrogen $\text{mg m}^{-2}\text{d}^{-1}$	C % of Seston	C:N Weight	C:N Atom	PPC $\mu\text{g m}^{-2}\text{d}^{-1}$	FPC $\mu\text{g m}^{-2}\text{d}^{-1}$
1	100	13./15.09.	48	27.8	0.58	x	38.4	16.48	2.62	42.9	6.3	7.3	28.6	42.9
3	125	18./19.09.	22.7	6.6	0.3	x	19.6	6.86	1.35	30.0	5.1	5.9	6.7	16.7
5	100	22./23.09.	36.1	7.4	0.2	x	23.2	9.07	1.83	39.1	4.9	5.8	0.3	15.8
	100						x 20.2	3.71	0.54	18.4	6.9	8.0	3.9	5.3
	500	22./23.09.	31.4	0.9	0.02	x	41.0	1.49	0.08	3.6	19.2	22.4	3.7	0
7	50	26./27.09.	21.4	13.9	0.66	x	87.4	39.58	5.90	45.3	6.7	7.8	7.6	434.4
	50						x 31.8	9.04	1.50	28.4	6.0	7.0	23.0	4.3
	500	26./27.09.	21.5	10.1	0.47	x	87.4	17.95	2.31	20.5	7.8	9.1	2311.6	8.2
9	50	01./02.10.	33.6	5.7	0.17	x	183.5	46.37	7.13	25.3	6.5	7.6	-	-
	50						x 125.4	37.16	5.45	29.6	6.8	7.9	874.5	338.4
	500	01./02.10.	24.9.	5.4	0.22	x	255.0	30.30	3.77	11.9	8.0	9.4	2961.1	68.9
14	75	04./05.10.	25.6	16.9	0.66	x	90.7	29.03	3.88	32.0	6.6	7.7	141.9	13.6
	75						x 39.1	8.44	1.38	21.6	6.1	7.1	47.4	265.2
	500	04./05.10.	25.6	10.6	0.41	x	29.1	4.86	0.93	16.7	5.2	6.1	57.2	30.6
16	50	07./08.10.	26.8.	13.9	0.52	x	660.1	123.50	25.79	18.7	4.8	5.6	1423.0	109.8
	50						x 254.7	68.52	11.22	26.9	6.1	7.1	492.5	184.2
16A	50	07./08.10.	35.3	16.0	0.45	x	513.3	207.38	32.14	40.4	6.5	7.5	-	-
B	50					x	1085.1	220.94	34.04	20.4	6.5	7.6	-	-
C	50					x	141.2	45.40	7.88	32.2	5.8	6.7	-	-
D	50					x	173.1	33.61	7.16	19.4	4.7	5.8	-	-
E	50					x	142.9	53.20	10.37	37.2	5.1	6.0	-	-
F	50					x	123.2	43.38	10.31	35.2	4.2	4.9	-	-

Table 3

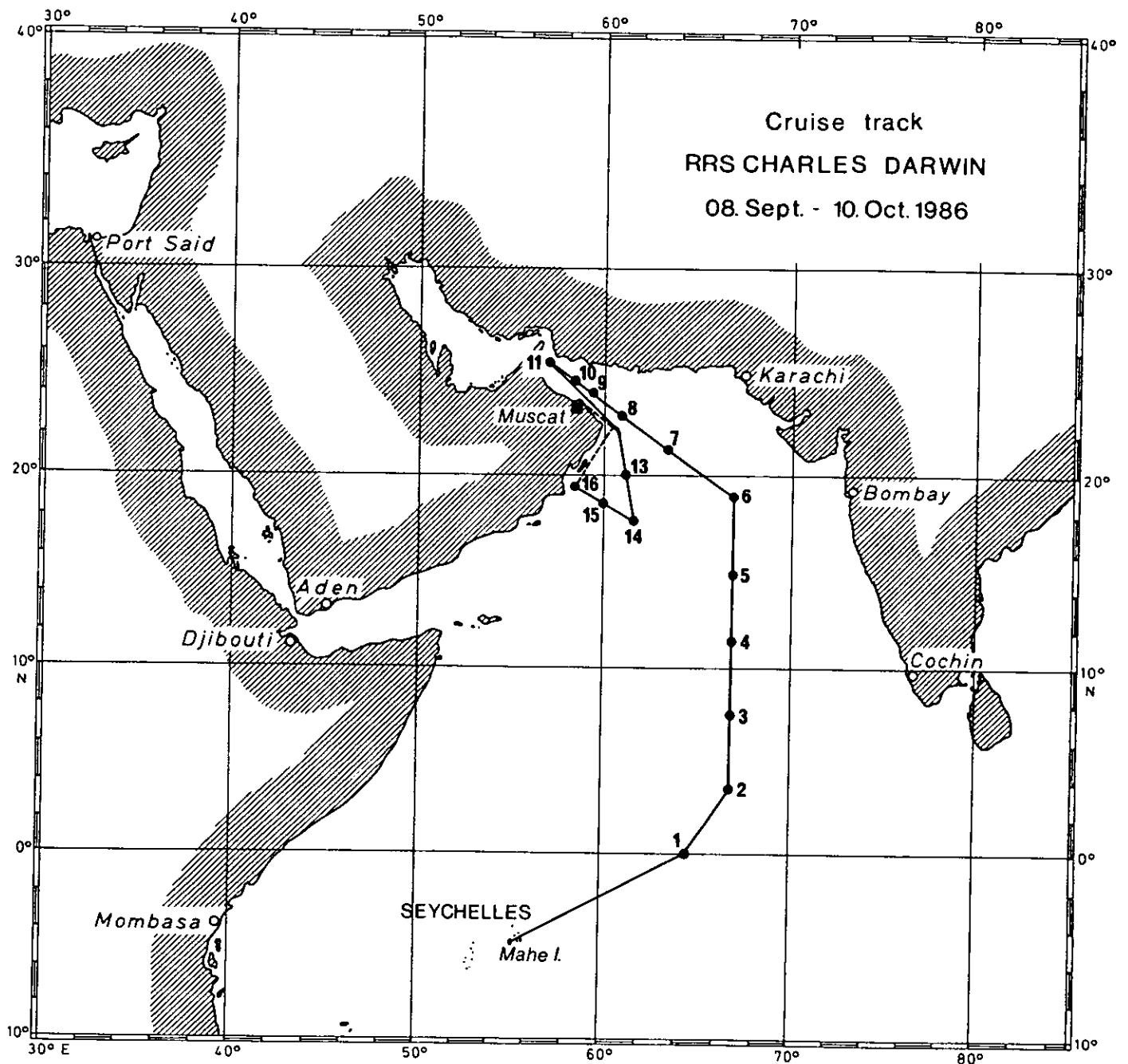
Integrated Primary Production. North-western Indian Ocean, Sept/Oct., 1986

Station	Date	mg C m ⁻² d ⁻¹	%>5 μ m	%<5 >0.8 μ m	%<0.8>0.2 μ m	av.Chlor.
1	13th Sept	533.0	60	22	18	0.19
1	14th Sept	413.3	26	36	38	0.19
3	18th Sept	364.2	30	35	36	0.17
3	19th Sept	236.4	19	43	39	0.18
5	22nd Sept	421.3	27	44	29	0.40
5	23rd Sept	511.2	19	58	23	0.35
7	27th Sept	449.3	38	49	13	0.65
9	2nd Oct	726.4	20	70	10	0.63
14	5th Oct	1391.2	57	31	12	1.63
16	7th Oct	2667.9	90	6	4	1.66

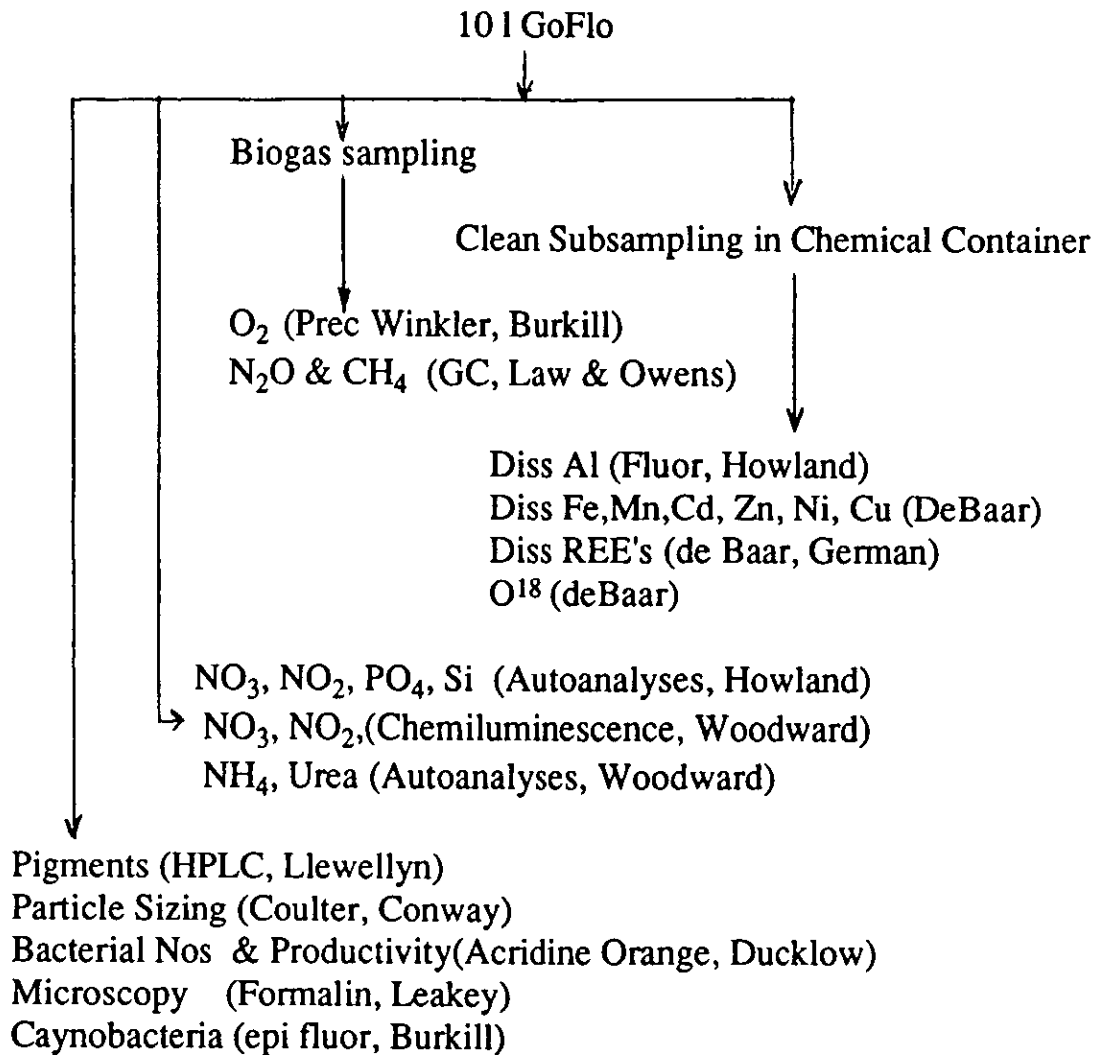
Table 4**Undulating Oceanographic Recorder Towing Data
- Indian Ocean R R S Darwin CD16/86**

DATES	ROUTE	TOW #	TOW LENGTH (n miles)
9.9.86	Shdn -> Seych	98601	24
11.9.86	Seych -> St 1	98602	27
		98603	25
15.9.86	St 1 -> St 2	98604	55
		98605	154
16.9.86	St 2 -> St 3	98606	122
		98607	82
19.9.86	St 3 -> St 4	98608	210
21.9.86	St 4 -> St 5	98609	144
24.9.86	St 5 -> St 6	98610	190
25.9.86	St 6 -> St 7	98611	222
27.9.86	St 7 -> St 8	98612	168
28.9.86	St 8 -> St 10	98613	165
30.9.86	St10 -> St 11	98614	55
30.9.86	St 11 -> St 9	98615	144
2.10.86	St 9 -> St 13	98616	lost UOR

Figure 1: Cruise Track and Station positions of R R S Charles Darwin in the northwestern Indian Ocean.



**Figure 2; Analytical Splits of water samples from rosettes bottles of the CTD-
'Biogeochemical Casts' listed in Table 1.**



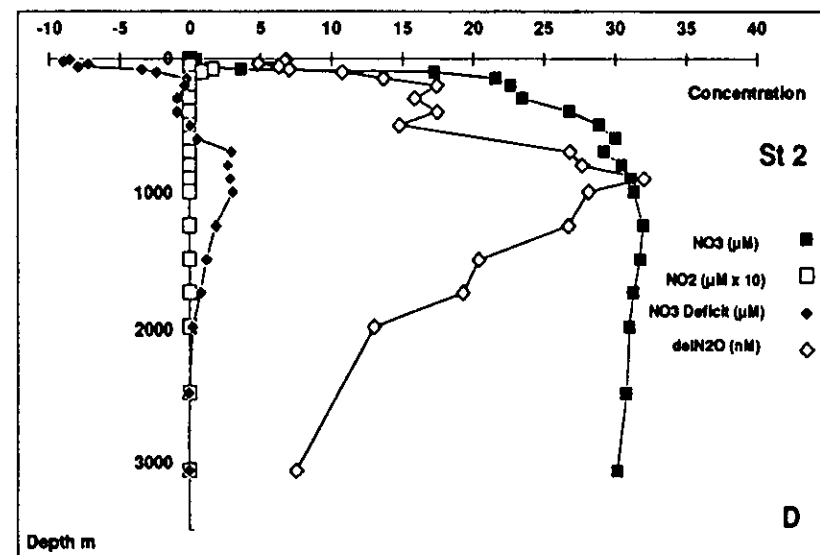
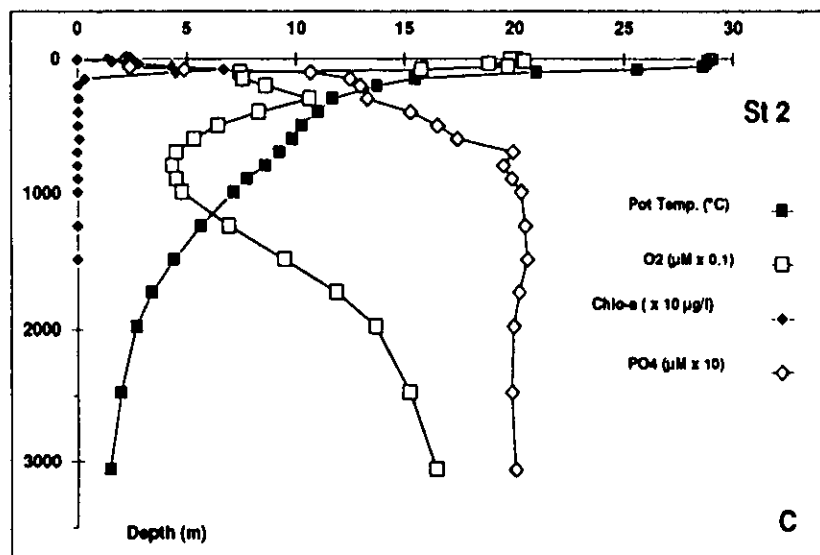
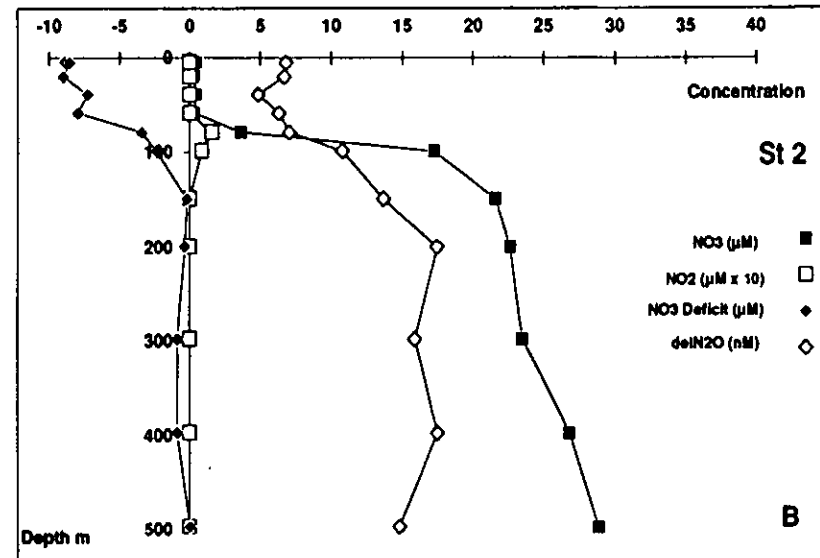
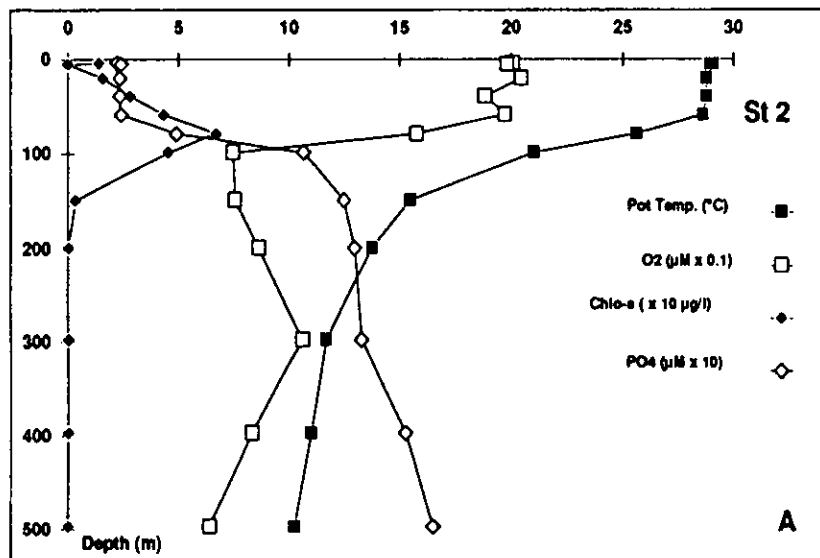


Figure 3: Typical vertical profiles for potential temperature, chlorophyll, nutrients, oxygen, nitrous oxide and nitrate deficits for St 2 of the NWIO (Mantoura et al 1992)

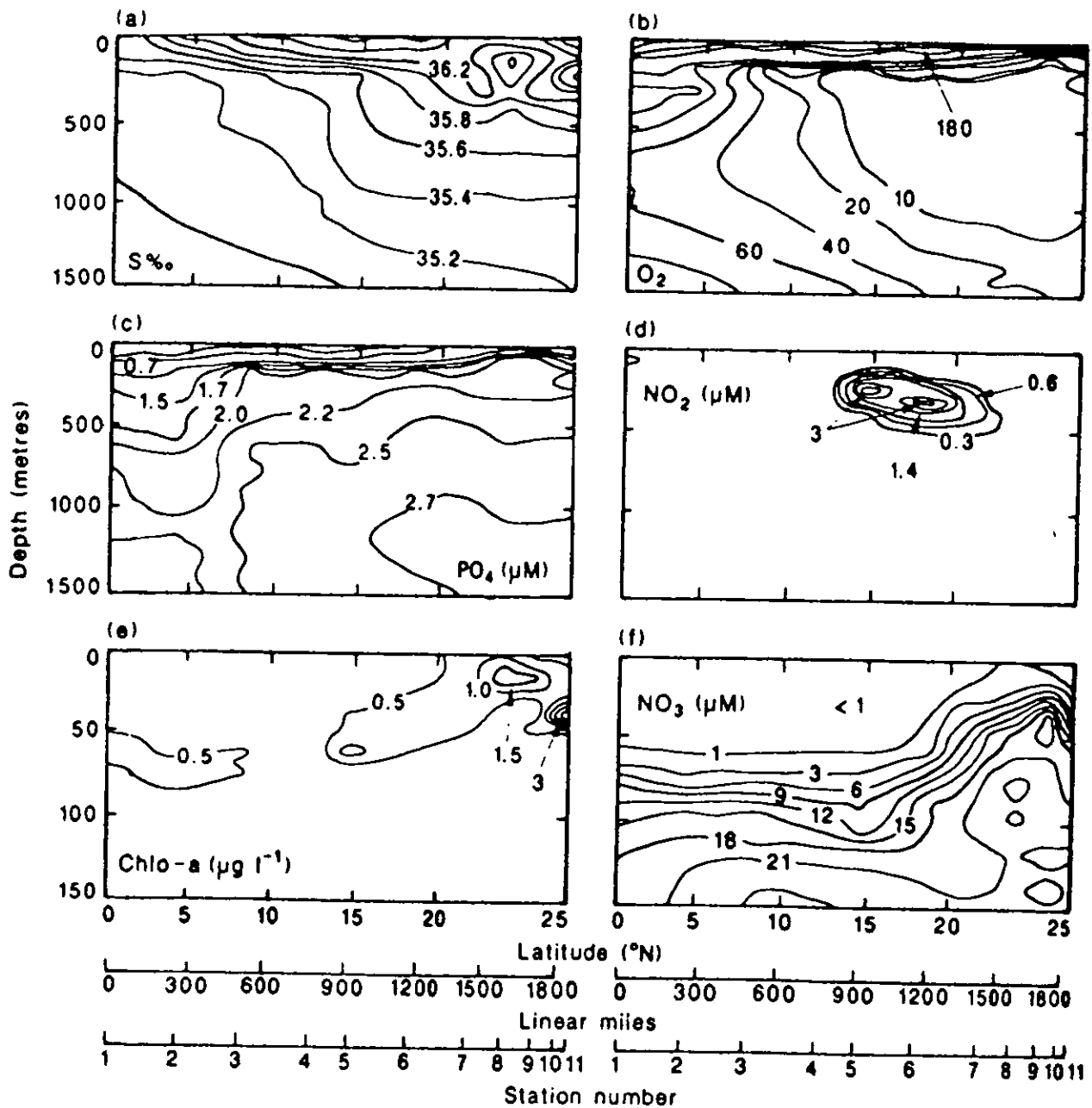


Figure 4:

Chemical oceanographic sections of St 1-11 for salinity ($^{\circ}/_{\infty}$, a), oxygen (μM , b), phosphate (μM , c), nitrite (μM , d) for the upper 1500 m, and for nitrate (μM , f) and chlorophyll-a ($\mu\text{g}/\text{l}$, e) for the upper 150 m

Mantoura et al (1992)

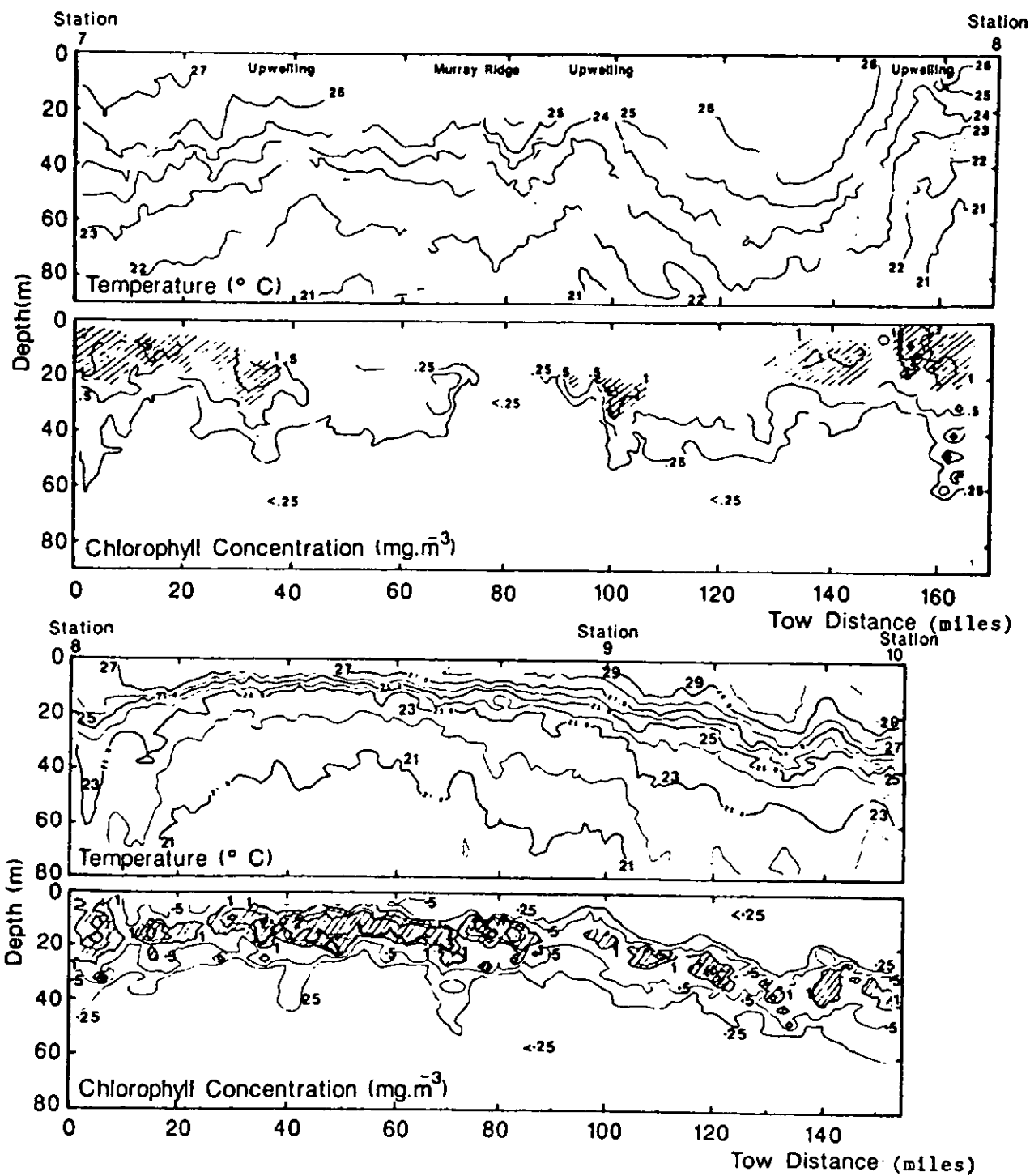
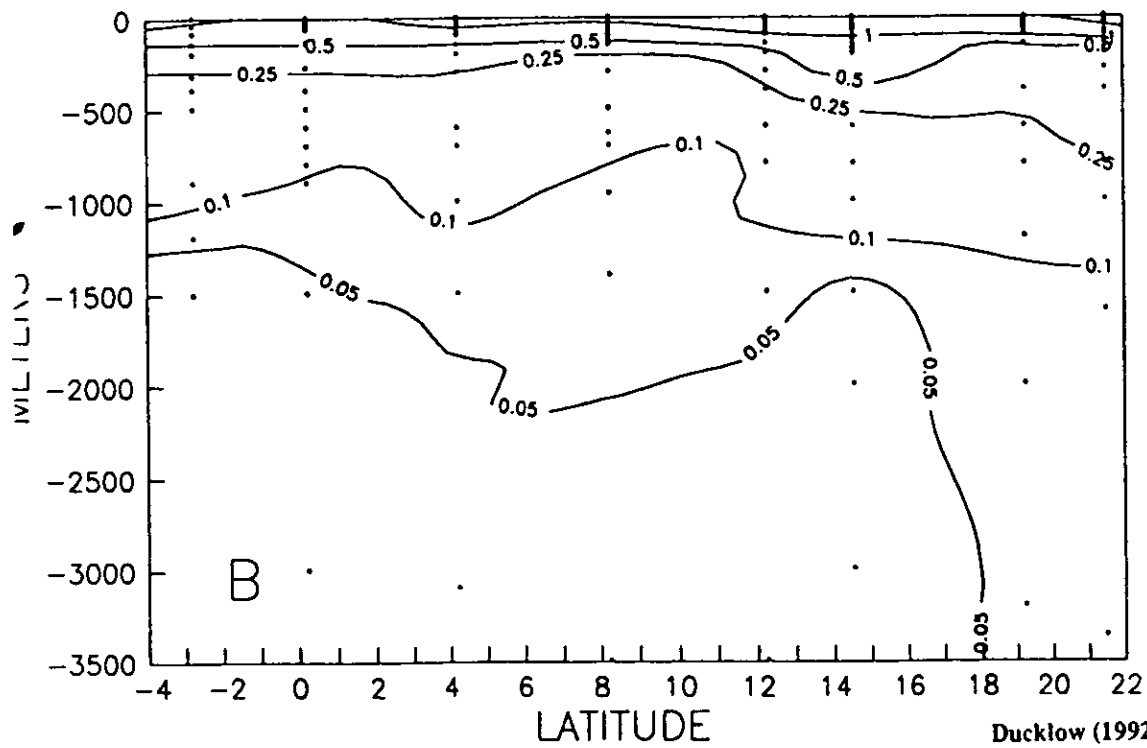
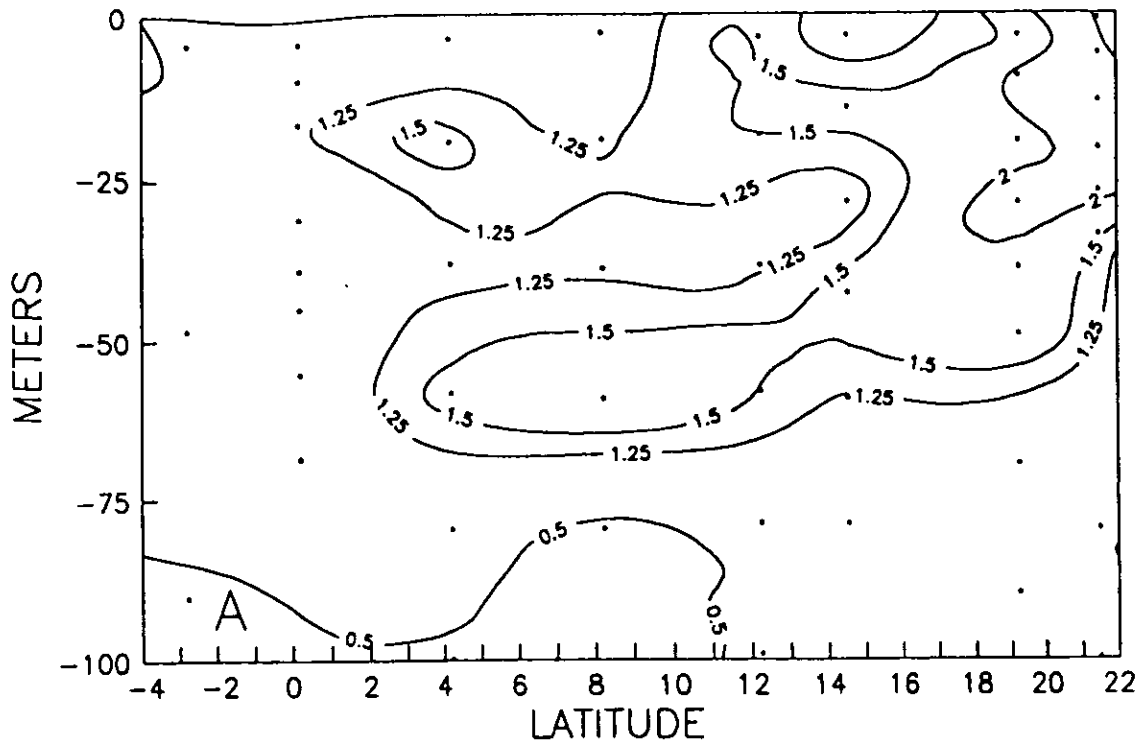


Figure 5: Undulating Oceanographic Recorder (UOR) sections for tow 12 (stations 7 to 8) and tow 13 (stations 8 to 10): a) Temperature, tow 12; b) Chlorophyll concentration, tow 12; c) Temperature, tow 13; d) Chlorophyll concentration tow 13. Owens et al (1992)



Ducklow (1992)

Figure 6: Contour plots of bacterial abundance (10^9 cells per liter) for A) the upper 100 m and B) full water column along transect from stations 0-7. Dots represent sample depths from which data were contoured.

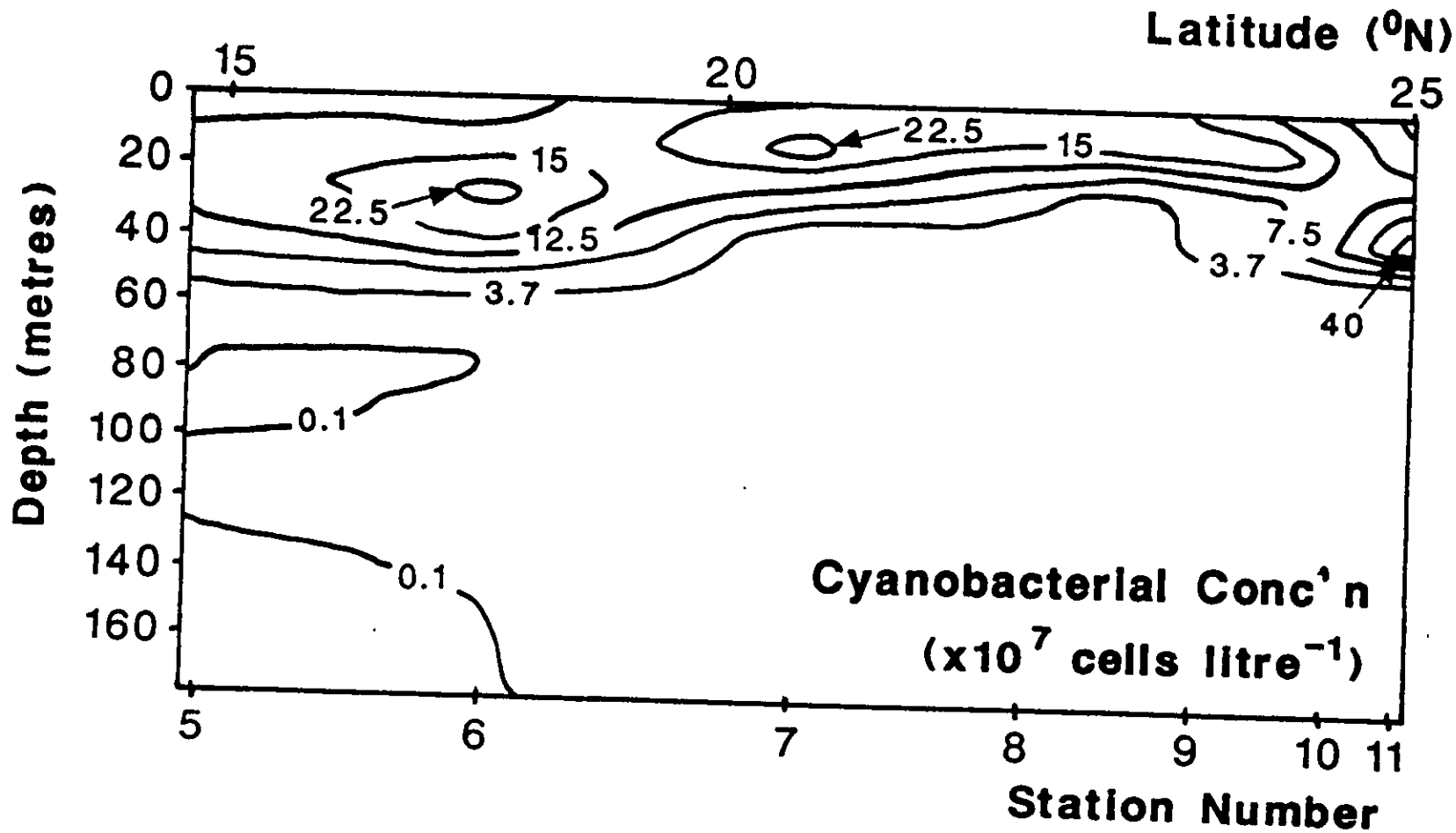
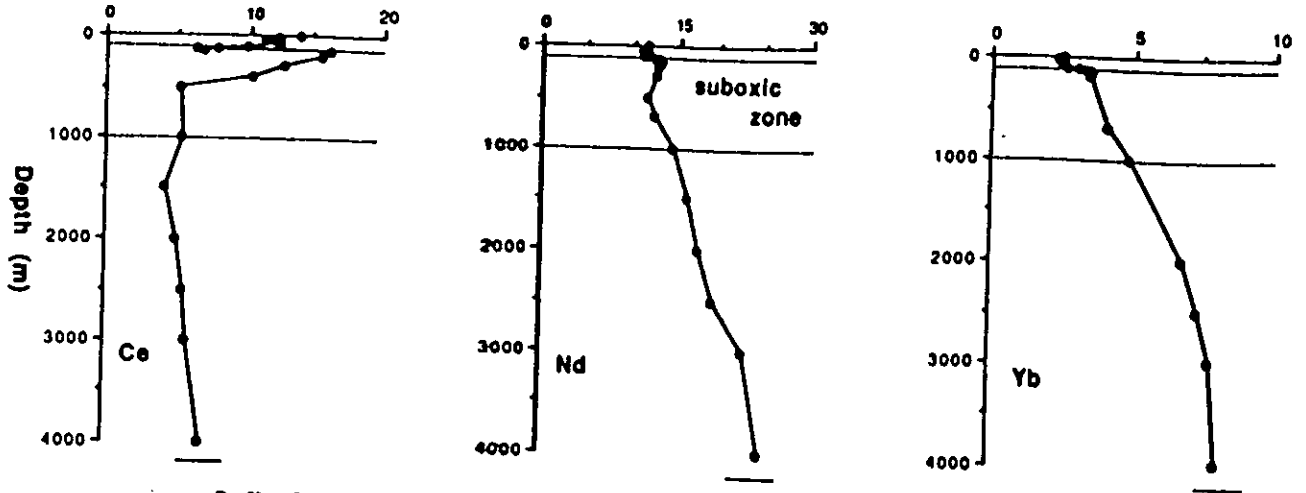


Figure 7: Cyanobacterial depth distribution along a transect between station 5 in the Arabian Sea and station 11 at the Straits of Hormuz.

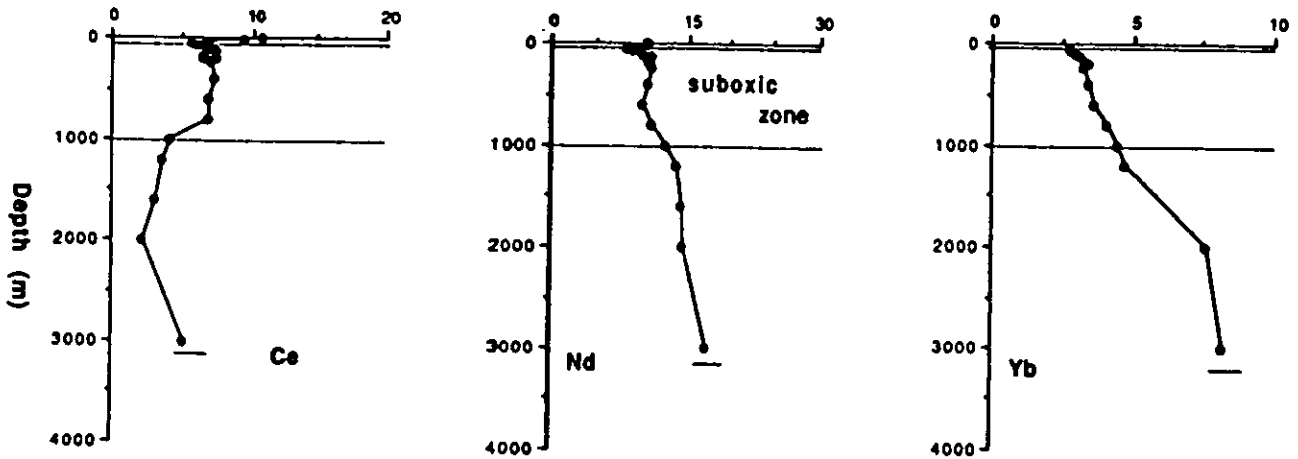
Burkill et al (1992)

Dissolved REE (pmol/kg): Station 1605



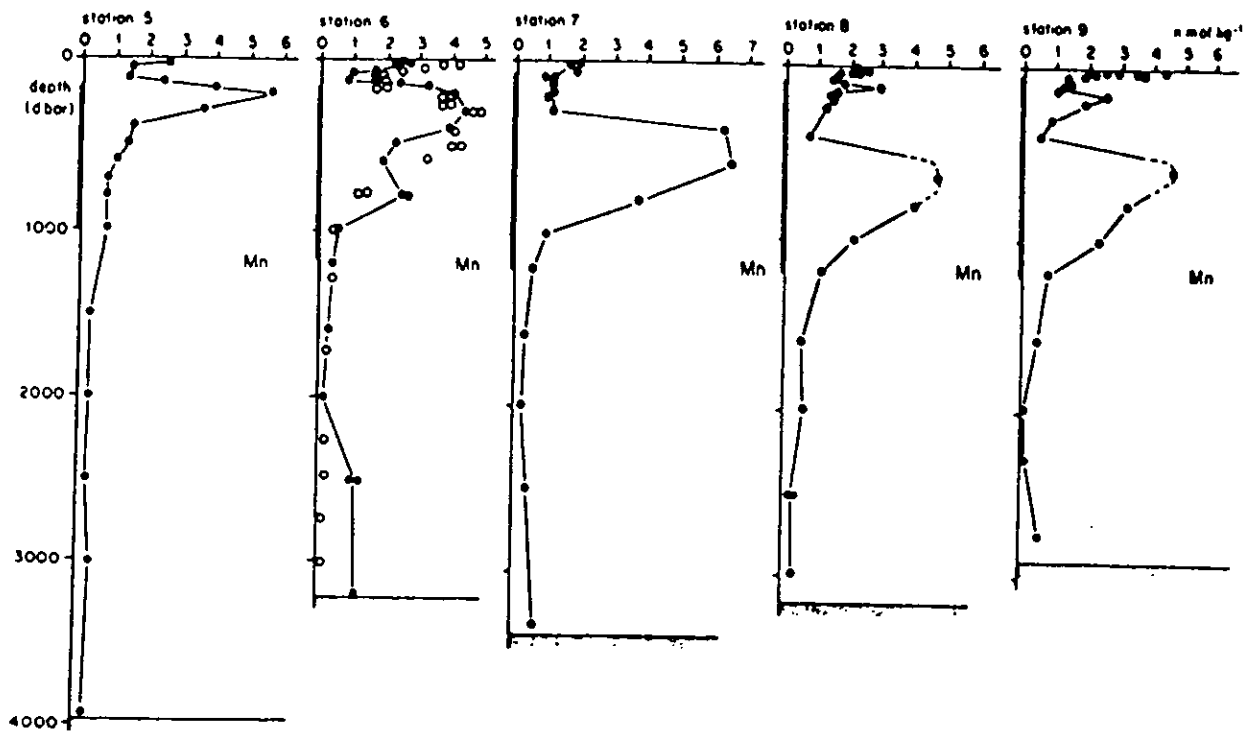
Profiles of dissolved Ce, Nd, and Yb concentrations (pmol/kg) at station 1605 in the NW Indian Ocean.

Dissolved REE (pmol/kg): Station 1608



Profiles of dissolved Ce, Nd, and Yb concentrations (pmol/kg) at station 1608 in the NW Indian Ocean.

Figure 7: German and Elderfield (1990)



Vertical profiles of dissolved Mn for Stations 5-9. Also shown in this figure is the Mn profile at Station VERTEX-II (2) in the east equatorial Pacific (from LANDING and BRULAND, 1987). The solid bar at the depth axis denotes the oxygen minimum zone.

Figure 8: Saager et al (1989)

Nitrogen Biogeochemical Cycling in the northwestern Indian Ocean

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ABSTRACT

The vertical distribution and fine scale structure of nitrate (NO_3), nitrite (NO_2), nitrous oxide (N_2O), phosphate (PO_4), oxygen (O_2) and chlorophyll-*a* were determined in the North Western Indian Ocean (NWIO) along a meridional section (67°E) from the Equator to the Gulf of Oman using an Autoanalyser for micromolar levels of nutrients, and novel chemiluminescence and gas chromatographic methods for nanomolar levels of NO_3 and NO_2 and N_2O respectively. Three biogeochemically contrasting regimes were investigated: (1) the highly oligotrophic nutrient-depleted subtropical gyre, (2) the monsoonal upwelling of nutrient-rich intermediate waters off the S E Arabian Coast and (3) the denitrifying O_2 -depleted zone (ODZ) (ca 150 - 1200 m depth) in the Arabian Sea.

Concentrations of NO_3 and NO_2 were severely depleted in surface oligotrophic waters from the equator (ave. 43 and 3.6 nM respectively) to the subtropical gyre ($12\text{-}15^\circ\text{N}$; ave. 13.3 and 2.0 nM respectively) with similar levels in the more stratified Gulf of Oman. Upwelling waters off Southern Arabia had three orders of magnitude higher NO_3 levels, and throughout the NWIO, the calculated NO_3 -fuelled primary production appeared to be regulated by NO_3 concentration.

Existing Redfield $\Delta\text{O}_2/\Delta\text{NO}_3$ regeneration ratios (≈ 9.1) previously derived for the deep Indian Ocean were confirmed (≈ 9.35) within the oxic upper layers of the NWIO. The 'NO'-potential temperature relationship (BROECKER, 1974) needed for the derivation of expected NO_3 and NO_2 -deficits within the denitrifying ODZ were refined using an isopycnal, binary mixing model along the $\sigma_\theta = 26.6$ $^\circ/\infty$ density layer to take into account the inflowing contribution of NO_3 -depleted Persian Gulf Water. Vertically integrated NO_3 -deficits increased northwards from 0.8 mol $\text{NO}_3\text{-N m}^{-2}$ at St 2 (04°N) up to 6.49 mol $\text{NO}_3\text{-N m}^{-2}$ at St 9 at the mouth of the Gulf of Oman, then decreased to 4.10 $\text{NO}_3\text{-N m}^{-2}$ toward St 11 near the Straits of Hormuz. When averaged for the denitrification area of the Arabian Sea, this corresponds to a deficit of 118 Tg $\text{NO}_3\text{-N}$. Adopting a recent Freon-11 based estimate of water residence time of 10 years (OLSON *et al*, 1991) for the O_2 -depleted layer, we calculate an annual net denitrification flux of 11.9 Tg N to the atmosphere or approximately 10 % of the global water column denitrification rates.

Supersaturated N_2O concentrations were found in both surface oxic and upwelling waters (up to 246 %) and peaked at the base of the ODZ (up to 1264 %) in the northern Arabian Sea. Both nitrification in oxic waters and denitrification in hypoxic layers can be invoked as sources of N_2O . The inventory of excess N_2O amounted to 2.55 ± 1.3 Tg $\text{N}_2\text{O-N}$ corresponding to annual production of 0.26 ± 0.13 Tg from denitrification. This is comparable to earlier (LAW and OWENS, 1990) estimates of the ventilation flux of N_2O (0.22 - 0.39 Tg/year) from the upwelling region of the Arabian Sea. The decadal response times for circulation, deoxygenation, denitrification and ventilation of the ODZ-derived N_2O and CO_2 greenhouse gases and their monsoonal coupling implies the Arabian Sea is a sensitive oceanic recorder of global climate change.

Size fractionated primary production and nitrogen assimilation in the northwestern Indian Ocean

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Abstract

Rates of phytoplankton production and nitrogen assimilation were measured at various stations along a transect in the northwestern Indian Ocean from near the equator, northwards into the upwelling system off the Arabian peninsula, during September/October 1986. The measurements were made using *in situ* incubation techniques with the simultaneous use of ^{14}C and ^{15}N isotopes. Samples were fractionated after the incubations into three size classes: 0.2-0.8 μm ; 0.8-5.0 μm ; >5.0 μm for the ^{14}C incubations, and <5.0 μm and >5.0 μm for the ^{15}N incubations. The assimilation of nitrate and ammonium was measured. These measurements were supported by a detailed description of the horizontal and vertical distributions of chlorophyll, temperature and underwater light field by the deployment of a towed undulating oceanographic recorder. Rates of primary production ranged from approximately 0.5 g C m⁻² d⁻¹ at the equator, reducing to <0.3 in the oligotrophic gyre in the central northern Indian Ocean, and to >2.5 in the upwelling region off the coast of Oman; total nitrogen assimilation followed a similar pattern. Very significant variations in the size distribution of the activity of the plankton were observed. Over 75% of the carbon and nitrogen assimilation was in the < 5 μm fraction at the south of the transect; this decreased to approximately 10% in the upwelling region. New production (*f* ratios) varied between approximately 0.1 in the oligotrophic regions to 0.9 in the upwelling region.

Methane production and flux to the atmosphere in the Arabian Sea.

In Press in NATURE

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Atmospheric methane has increased over the last few decades^{1,2}, and has been implicated as a contributor to global-warming. Although attention has been focused on anthropogenic sources, ice-cores show that major changes in atmospheric methane concentrations have occurred over glacial-interglacial time scales, indicating that there is significant variability in natural fluxes^{3,4}. Methane is frequently super-saturated in the surface waters of the oceans, indicating that they are a net source. Here we report high concentrations of methane, in the Arabian Sea, and calculate fluxes to the atmosphere up to five times greater than the previously reported highest ocean flux, and one to two orders of magnitude greater than many others. The methane is associated with elevated phytoplankton biomass which is coupled closely with monsoon-driven upwelling. We calculate that this region (representing 0.43% of the surface area of all the oceans) could account for between 1.3 and 133% of the current estimates of the open ocean source of methane. This disproportionate importance and link with the monsoons suggests that the Arabian Sea may be an oceanic region particularly sensitive to climate change with the potential for feedback responses greater than its surface area suggests.

For submission to a special edition of *Deep-Sea Research* on

Biogeochemical Cycling in the Indian Ocean.

***Synechococcus* and its importance
to the
microbial foodweb of the northwest Indian Ocean**

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The abundance, distribution, size, biomass, growth and grazing-induced mortality of phycoerythrin (PE) rich chroococcoid cyanobacteria were studied during September/October 1986 in the Arabian Sea, the Gulf of Oman and the monsoonal upwelling region off the South East Arabian coast. Cyanobacteria were abundant ($>10^7$ cells litre⁻¹) through the region and particularly so ($>10^8$ cells litre⁻¹) in oligotrophic waters where they exhibited distinct sub-surface concentration maxima which were situated above but related to the depth of the chlorophyll maxima. Cell diameter increased from 0.7 μm in surface waters to 1.2 μm at depth. Standing stocks of cyanobacteria ranged upto 50 μgC litre⁻¹, and accounted for upto 40% of the POC in oligotrophic stations indicating that *Synechococcus* constitutes an important trophic resource. Experimental investigations showed that cyanobacterial populations were growing fast with specific growth rates of 0.5-1.0 day⁻¹ while simultaneously experiencing high mortality due to microzooplankton grazing. Grazing rates varied between 0.3 and 1.2 day⁻¹, indicating that 31 to 71% of the cyanobacteria were predated daily. Grazing and cyanobacterial growth were correlated suggesting that *Synechococcus* production and its fate by microbial grazing activity were tightly coupled. Cyanobacteria are clearly a major component of a dynamic but well-balanced microbial foodweb present in oligotrophic regions of the northwest Indian Ocean.

Bacterioplankton distributions and production in the Northwestern
Indian Ocean and Gulf of Oman, September, 1986

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ABSTRACT

Bacterial abundance and ³H-thymidine incorporation were measured throughout the water column during September-October, 1986 along transects in the NW Arabian Sea and Gulf of Oman. Bacterial abundances and production estimated from incorporation rates were high ($>1 \times 10^9$ cells per liter and 30-92% of primary production, respectively) along the oceanic portions of the transects. These elevated levels may indicate a response to the decline of summer phytoplankton blooms stimulated by monsoonal deepening of the mixed layer. Bacterial production and abundance profiles had complex vertical structure with multiple subsurface maxima related to chlorophyll and oxygen distributions. Production and abundance both declined exponentially with depth below 100-200 m. Rates of dissolved organic carbon (DOC) release from the sinking particle flux may have been adequate to support bacterial production in the Gulf of Oman, but in the open Arabian Sea this source appeared to be insufficient to meet the bacterial demand. The bacterial production estimates reported herein are very conservative because very low conversion factors were used. In general these results suggest that the factors usually assumed to support bacterial production (e.g., phytoplankton exudation, particle breakdown) supply only a fraction of the bacterial demand in the NW Indian Ocean.

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Significant flux of atmospheric nitrous oxide from the northwest Indian Ocean

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INTEREST in nitrous oxide (N_2O) has increased considerably in the light of its deleterious effect on the ozone layer¹, and contribution to the greenhouse effect². There are many sources of atmospheric N_2O , both anthropogenic (for example, combustion) and natural, but the global budget is still inadequately defined. Despite the fact that most of the world's oceans are close to equilibrium with the atmosphere³, water bodies depleted in oxygen have been identified as areas of N_2O production^{4,5}, and so the oceans represent a potential source of atmospheric N_2O . Here we report elevated N_2O concentrations in the northwest Indian Ocean, an area that exhibits upwelling and high oxygen consumption in the water column. We found that N_2O was supersaturated in both oxygen-saturated surface waters (up to 246% N_2O saturation) and oxygen-depleted sub-surface waters (1,264% N_2O saturation). The calculated flux to the atmosphere indicated that upwelling in the northwest Indian Ocean (15–25° N) represents one of the most significant marine sources of N_2O , contributing between 5 and 18% of the total marine flux from a surface area of only 0.43% of the world ocean. These data suggest that the oceanic flux of N_2O to the atmosphere shows strong spatial heterogeneity which should be considered in global budgets and ocean-atmosphere models.

A transect of the northwest Indian Ocean (Fig. 1) was followed from close to the Equator (00°04' N 65°05' E), across the Arabian Sea into the Gulf of Oman (24°49' N 57°13' E) during September–October 1986. Vertical profiles of dissolved N_2O (and other oceanographic variables) were obtained at 16 stations by sampling at 20–24 depths between the surface and 4,000 m. This region exhibits two important oceanographic features: (1) a monsoon-driven upwelling, located off the Arabian Peninsula; (2) sub-surface waters that are persistently severely depleted in oxygen⁶. The upwelling is dominant during June–August when the southwesterly winds average 10–11 $m s^{-1}$; whereas the rest of the year is characterized by a mean wind speed of 4 $m s^{-1}$ (Meteorological Office, Bracknell, UK) with reduced upwelling. The water column was generally supersaturated with N_2O with respect to an atmospheric N_2O concentration of 303.9 parts per 10⁹ by volume (ref. 3, with subtraction of 0.2% to account for the annual increase in atmospheric N_2O); the data are therefore considered in terms of ΔN_2O , which represents the excess N_2O over that which would be in equilibrium with the atmosphere. Dissolved oxygen concentrations are presented in terms of the apparent oxygen utilization, AOU (the difference between the equilibrium oxygen concentration at ambient temperature and salinity and the observed oxygen concentration), which is a measure of the degree of oxygen depletion.

Figure 1 shows the N_2O -depth distribution from stations 1 to 11. All profiles exhibited a similar trend with an increase in ΔN_2O between 200 and 1,000 m, coincident with the oxygen minimum. ΔN_2O maxima of >45 $nmol l^{-1}$ were recorded in the upwelling region (stations 6–16), and also at station 3 where lower-salinity surface water, originating from the region of the Equator, dipped below water of elevated salinity originating from the Gulf of Oman. The average ΔN_2O supersaturation of all samples ($n=309$) was 302%, with a maximum of

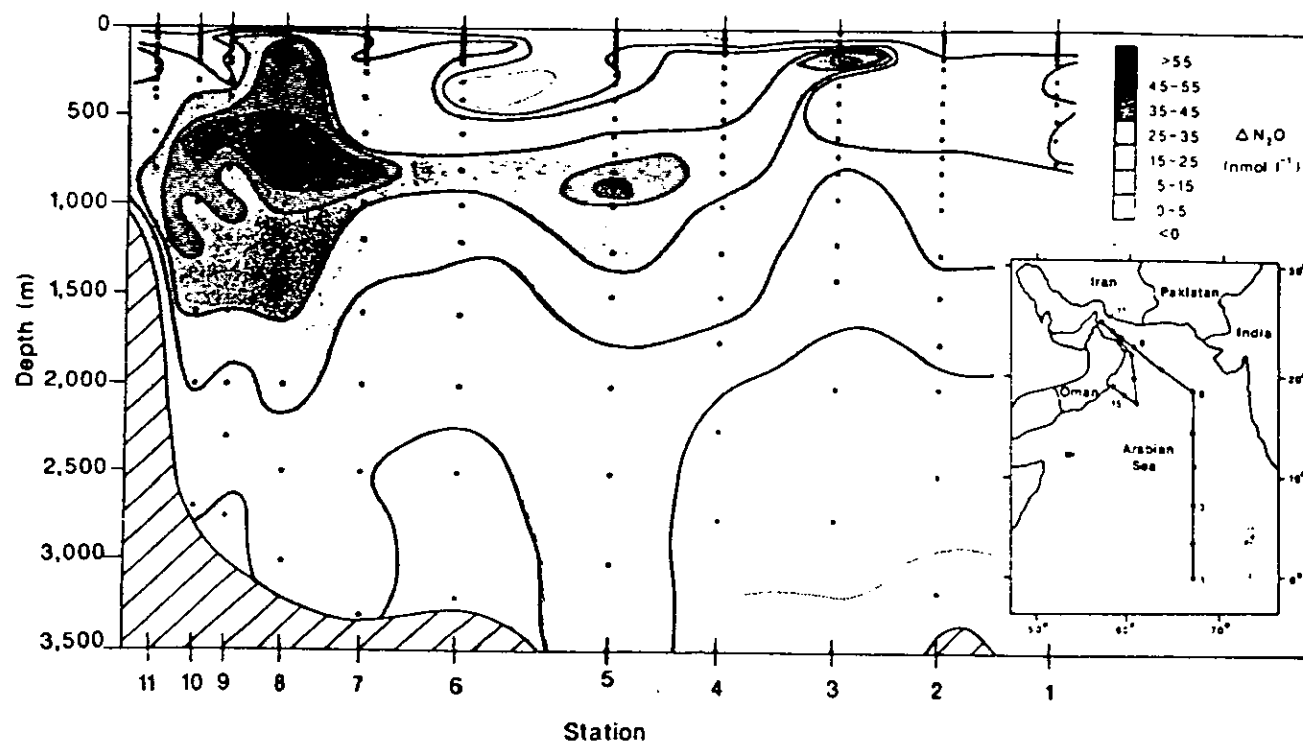


FIG. 1 ΔN_2O depth distribution along a transect from station 1 at the Equator to station 11 in the Gulf of Oman (see inset). Water samples (20–24 depths from the sea surface to the bottom) were obtained by Go-Flo oceanographic bottles and subsampled immediately under nitrogen. Dissolved N_2O was extracted immediately by a static vacuum technique²³. In brief, water samples were drawn into an evacuated 500-ml gas sampling bulb through a narrow constriction, which facilitated the dissociation of the gas and liquid phase. After attaining atmospheric pressure, 1-ml aliquots of the headspace were removed and analysed by electron capture detector/gas chromatogra-

phy (Varian, 2 m \times 3 mm outer diameter Porapak Q column, with a precolumn of drierite and carbosorb; column at ambient temperature, detector 320 °C; high-purity N_2 carrier at flow rate 30 $ml min^{-1}$). Calibration and efficiency of the extraction technique was determined by analysing sea water of known N_2O . The standard deviation of the gas chromatographic analysis was 1.4%, and the relative standard deviation of the entire analysis was 3.8%. N_2O (99.5% purity) for calibrations obtained from Bedford Technical Instruments Ltd.

Rare earth elements in the NW Indian Ocean*

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Abstract—Dissolved rare earth element (REE) distributions have been determined at three stations in the high productivity NW Indian Ocean (NWIO) upwelling zone. Dissolved REE distributions within the well-oxygenated surface waters and deep portions of the water column are similar to those reported previously from other open-ocean locations. At depth, dissolved REE concentrations are intermediate between those of the Atlantic and Pacific Oceans, consistent with the continuous regeneration and enrichment of the strictly trivalent REEs in, and the progressive oxidative removal of Ce from, the deep ocean. Within the mid-depth oxygen minimum zone dissolved REE concentrations exhibit a notable enrichment superimposed upon these "typical" oceanic profiles. Further, dissolved Ce concentrations are preferentially enriched within the suboxic horizon compared to the rest of the series, indicating the reduction of insoluble Ce(IV) to dissolved Ce(III) at these depths. By analogy with our previous studies of REE distributions in anoxic basins we propose that the more modest enrichments of the strictly trivalent REEs observed in the NWIO suboxic zone must derive from uptake through scavenging within the well-oxygenated portions of the water column and regeneration from sediments and settling particles within the more reducing conditions of the oxygen minimum zone.

INTRODUCTION

IN A RECENT INVESTIGATION of the behaviour of the rare earth elements (REEs) in the Cariaco Trench we demonstrated that distributions of the entire rare earth series (and Ce in particular) exhibit marked variations across the boundary between oxic and anoxic waters (DE BAAR et al., 1988). Dissolved REE concentrations increased markedly with increasing depth across the oxic/anoxic interface whilst particulate REE concentrations exhibited complementary negative concentration gradients across the same depth interval. Subsequently we have demonstrated similar variations in REE distributions in a study of Saanich Inlet, British Columbia, but the pronounced dissolved and particulate REE concentration gradients were observed in the *suboxic* portion of the water column, some 10–40 m above the O₂/H₂S interface (GERMAN and ELDERFIELD, 1989). In both locations, however, the strong REE concentration gradients were coincident with strong concentration gradients of dissolved and particulate Mn. Because the standard free energy changes associated with MnO₂ and CeO₂ reduction are similar (ELDERFIELD and SHOLKOVITZ, 1987) it seems that Ce concentrations in these two basins are dominated by the oxidative-precipitation/reductive-dissolution cycle of Ce, directly analogous to that of Mn, whilst distributions of the other REEs, which are strictly trivalent in seawater and exhibit no intrinsic redox chemistry, are controlled by secondary adsorption/desorption processes associated with the primary dissolution/precipitation cycle of ferromanganese oxyhydroxides.

In this study we have extended these investigations by examining the behaviour of dissolved rare earth elements in the northwest Indian Ocean (NWIO) upwelling zone. High

productivity in this region leads to strong oxygen depletion at depth, either through *in situ* consumption (due to the decay of settling organic material) or through interaction and reaction with reducing coastal sediments and subsequent advection of oxygen-depleted water off-shore. Thus, although conditions are not sufficiently extreme to promote permanent anoxicity, suboxic conditions (O₂ < 15 μmol/l) prevail across much of the region at depths between 100–150 m and approximately 1000 m—the oxygen minimum zone (SCLATER and KROOPNICK, 1984).

Similar sub-oxic conditions have been reported from the tropical E. Pacific where upwelling also promotes high biological productivity in the surface waters and resultant oxygen depletion at depth. Near-exhaustion of the available dissolved oxygen supply leads to the utilisation of alternative oxidants in the respirative decomposition of sinking organic matter: dissolved nitrate begins to be utilised as an alternative electron acceptor, undergoing reduction to nitrite and, eventually, to molecular nitrogen (CLINE and RICHARDS, 1972; CODISPOTI and RICHARDS, 1976). In addition, waters from the oxygen minimum zone of the tropical E. Pacific exhibit enrichment in dissolved Mn and Fe resulting from the reduction of relatively insoluble oxidised species *in situ* as they settle through the water column and also through release from the reducing pore waters of sediments in contact with the suboxic portion of the water column (see, e.g., KLINKHAMMER and BENDER, 1980; LANDING and BRULAND, 1980, 1987; MARTIN and KNAUER, 1980, 1984, 1985; MARTIN and GORDON, 1988).

Therefore, by analogy with the work in the equatorial Pacific, the NWIO would seem to be an ideal environment in which to test the proposal derived from studies of anoxic basins that REE cycling is associated with Mn cycling in the suboxic zone. Prior to this work, little study had been made of dissolved trace elements in the NWIO (DANIELSSON, 1980; FOWLER et al., 1984). Hence, it was decided to investigate the sensitivity of the REEs to the delicately poised suboxic

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Manganese and iron in Indian Ocean waters

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Abstract—The first vertical profiles of dissolved Mn and Fe for the (NW) Indian Ocean are reported. The area is characterized by seasonal upwelling and a broad oxygen minimum zone in intermediate waters. The dissolved Fe-profile exhibits a maximum (5.1 nM) in the oxygen minimum zone, with low values both in surface waters (0.3 nM) and deep waters (around 1 nM). Mn concentrations in the surface waters are elevated (2.0–4.3 nM), and decrease rapidly in an offshore direction. Below the first 25 m, concentrations decrease dramatically (0.5–1.3 nM), indicating removal by oxidation and particle scavenging. Further down, various Mn maxima are observed which can be related to hydrographic features (sigma- θ):

1. Intermediate water originating from the Red Sea lost its dissolved O₂ while flowing northward along the Omani coast and exhibits a strong Mn maximum (4.6–6.5 nM) coincident with the deep O₂ minimum.
2. At the two inshore stations in the Gulf of Oman this is overlain by relatively modest Mn maxima (± 2.7 nM) related to Arabian Gulf overflow water.
3. Finally the strong Mn maxima (4.4–5.6 nM) in the oxygen minimum zone at the two offshore stations are related to yet another watermass.

Below these various maxima, concentrations decrease gradually to values as low as 90 pM at 2000 meters depth. Towards the seafloor concentrations increase again, leading to a modest bottom water maximum (0.7–1.5 nM). The overall vertical distributions of Mn and Fe are strikingly similar, also in actual concentrations, to those previously reported for the eastern equatorial Pacific, an area also characterized by an extensive O₂-minimum zone.

INTRODUCTION

IN THE PAST DECADE our understanding of Mn in ocean waters has increased considerably. Distribution and fate in the Atlantic Ocean are dominated by atmospheric input (KREMLING, 1985; STATHAM and BURTON, 1986), intense scavenging at mid-depth (BENDER *et al.*, 1977) and fluxes from reducing shelf and slope sediments (KREMLING, 1983, 1985). The same processes influence the distribution and fate of Mn in the Pacific Ocean. In addition, the suboxic waters of the east equatorial Pacific are characterized by an intense dissolved Mn maximum (KLINKHAMMER and BENDER, 1980; LANDING and BRULAND, 1980, 1987; MARTIN and KNAUER, 1982, 1983, 1984, 1985; MARTIN *et al.*, 1985).

For Fe similar maxima are reported for the same east equatorial Pacific region (GORDON *et al.*, 1982; LANDING and BRULAND, 1987). In Pacific surface waters the very low, subnanomolar Fe levels appear to correlate with nutrients, hinting at the possible role of Fe as a limiting micronutrient (MARTIN and GORDON, 1988). For the north Atlantic, SYMES and KESTER (1985) report higher levels, typically increasing with depth to about 10 nM in bottom waters. The aforementioned overall dataset for Fe in the open ocean is still very limited due to contamination problems during sampling and analysis (LANDING and BRULAND, 1987; MARTIN and

GORDON, 1988). Here we report the first data for dissolved Mn and Fe in the Indian Ocean.

Continental inputs of Mn and Fe into the oceans occur via both fluvial (MARTIN and MEYBECK, 1979) and atmospheric pathways (HODGE *et al.*, 1978; DUCE, 1986; STATHAM and CHESTER, 1988). However, flocculation of Fe during the early stages of estuarine mixing often effectively removes virtually all Fe (>90%) and much of the Mn from river water (SHOLKOVITZ, 1976, 1978; GOLDSTEIN and JACOBSEN, 1988). Emanations from submarine hydrothermal vents cause elevated Fe and Mn concentrations which in the case of Mn can be traced for many miles away from the ridge crest before mixing and scavenging eventually erodes this signal (KLINKHAMMER *et al.*, 1986; HUDSON *et al.*, 1986). Otherwise the hydrothermal source only affects its direct surroundings, as reflected in the ferromanganese deposits on the flanks of the ridge (HEATH and DYMOND, 1977).

Both Mn and Fe are essential elements for phytoplankton growth (BRAND *et al.*, 1983). Under special oceanic conditions of ample nutrient (nitrate and phosphate) availability as encountered in the Southern Ocean, the subarctic North Pacific and upwelling areas, Mn and Fe may sometimes affect productivity (COALE and BRULAND, 1989; MARTIN and GORDON, 1988). Within the euphotic zone photochemical reduction of oxyhydroxides may maintain Mn and Fe in solution, available for phytoplankton uptake (SUNDA *et al.*, 1983; SUNDA and HUNTSMAN, 1988).

Throughout the oceanic water column Fe and Mn are removed via oxidative scavenging by biogenic or organically coated particles (BALISTRERI *et al.*, 1981; MARTIN and

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Cd, Zn, Ni and Cu in the Indian Ocean

Cd, Zn, Ni and Cu in the Indian Ocean

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ABSTRACT

Vertical profiles of dissolved Cd, Zn, Ni and Cu in the Northwest Indian Ocean (Arabian Sea) exhibit a nutrient type distribution as also observed in other oceans. The area is characterized by strong seasonal upwelling and a broad oxygen minimum zone in intermediate waters. However, neither Cd, Zn, Ni nor Cu appear to be affected by the reducing conditions, in contrast with earlier reported observations of Mn, Fe and Rare Earths Elements (REE) .

Low Cd/PO₄ ratios in surface waters of about 0.15 nM/μM are in good agreement with ratios typical of surface waters in other oceans. Deep water ratios, however, increase from 0.5 nM/μM to 0.85 nM/μM going inshore. These ratios are much higher than published for the deep North Atlantic and North Pacific Oceans, yet comparable to the high Cd/PO₄ ratio recently published for the Antarctic Ocean. Ratios of Zn/Si (0.062 nM/μM) are about the same as found in the Pacific Ocean. The ratios Ni/Si (0.054 nM/μM) are in good agreement with previous reports from the Indian Ocean. The Cu profile shows evidence of surface water inputs, regeneration in intermediate and deep waters and benthic fluxes and is further influenced by intensive scavenging, notably in surface waters.

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