

## Recent sedimentary records from the Arabian Sea

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**Abstract.** An attempt is made to understand the redox conditions that prevailed in the north eastern continental margins of the Arabian Sea and in the nearby deep water regions during the past few centuries using short undisturbed sediment cores. The geochronology is accomplished using  $^{210}\text{Pb}$  excess method and the proxy indicators chosen for productivity and associated redox changes are  $\text{CaCO}_3$ , organic matter (OM), Mn and U along with major elements Fe and Al. Such changes in principle are related to high productivity in the overlying waters which in turn depend on monsoonal intensity that causes upwelling responsible for increase in productivity. Alongwith the published data on gravity cores from the same region, our measurements suggest the following:

At  $\sim 300$  m water depth, south of  $21^\circ\text{N}$ , the sediment-water interface at depths of  $\sim 300$  m had been anoxic during the time span represented by the presently studied cores for approximately  $\sim 700$  y as evidenced by low Mn/Al ( $< 0.7 \times 10^{-2}$ ) and high U/Al ( $> 10^{-4}$ ) weight ratios. In some adjacent deeper regions, however, the environment turned oxic around  $\sim 200$  y BP. Whereas both Mn and Ra were lost to the overlying waters in the anoxic regions (depth  $\sim 340$  m), the Mn that diffused from deeper sections appears to have mineralized at the sediment-water-interface. Studies of this type on long undisturbed cores from the margins of the Arabian Sea and the Bay of Bengal, involving several proxies and geochronology by more than one method are needed to understand short term environmental (and monsoonal intensity) changes of the recent past with high resolution.

**Keywords.** Sedimentary records; Arabian Sea; lead 210; trace metals; productivity; monsoons.

### 1. Introduction

Past records of changes on earth and its environment, be they due to the position of our planet in the solar system relative to the Sun or due to accidents that would have taken place during the impact of objects from outer space on earth, can in principle be found either on land or under the oceans as marine deposits (Arrhenius 1963; Somayajulu 1990; IGBP 1990). Reference is made to Goldberg and Arrhenius (1958), Arrhenius (1963), Broecker and Peng (1982) and Faure (1986) for an account of chemistry, isotope systematics and geochronology of marine sediments. Whereas the continental records can be discontinuous and prone to erosion and weathering, those in ocean such as marine sediments are more continuous and undisturbed except for bioturbation caused by burrowing organisms in the top  $\sim 10$  cm (Goldberg and Koide 1962; Berger *et al* 1977; Krishnamurthy *et al* 1979). The marine sediments offer two types of paleo-records: (i) more recent ones (past few k.y.) with high resolution of  $\sim 10$  y and (ii) long-term records (resolution 5–10 ky) dating back to  $\sim 10^8$  yrs in principle but generally studied in detail up to the Quaternary. The continental margin (shelf and slope) sediments are best suited for studying the first type and the open ocean sediments provide the second type of record. The resolution and the length of the record depends on the sedimentation rate, sample thickness chosen, bioturbation

length and length of the sediment core available. The Indian Ocean, especially the northern half, is significantly different from the other oceans because of the monsoons. The south west (summer) and north east (winter) monsoons strongly influence productivity as well as the fresh water input from the Indian subcontinent. Arabian Sea, especially, is well known for its high productivity and associated oxygenation at intermediate depths (100–1000 m) where the waters are essentially saturated with oxygen (Qasim 1977; Naqvi *et al* 1990). One can, in principle, decipher the monsoonal intensities and associated fresh water input, upwelling and productivity etc. from the past records stored in the marine sediments using chemical tracers such as OM, Mn, U that are indicative of reducing conditions that set in due to monsoon season(s). Geochronological and/or geochemical studies have been carried out on the open Arabian Sea sediments (Prell 1984; Fontugne and Duplessy 1986; *et al* 1990, 1993). The basic requisites of these studies are: (i) collection of long sediment cores which are datable and (ii) identification and measurement of the various tracers/proxies diagnostic of a particular kind of 'change' in the environment. In an attempt to decipher the recent past records with high resolution, a study was initiated using the Arabian Sea sediments, the results of which are presented and discussed with emphasis on the potential of such studies.

## 2. Materials and methods

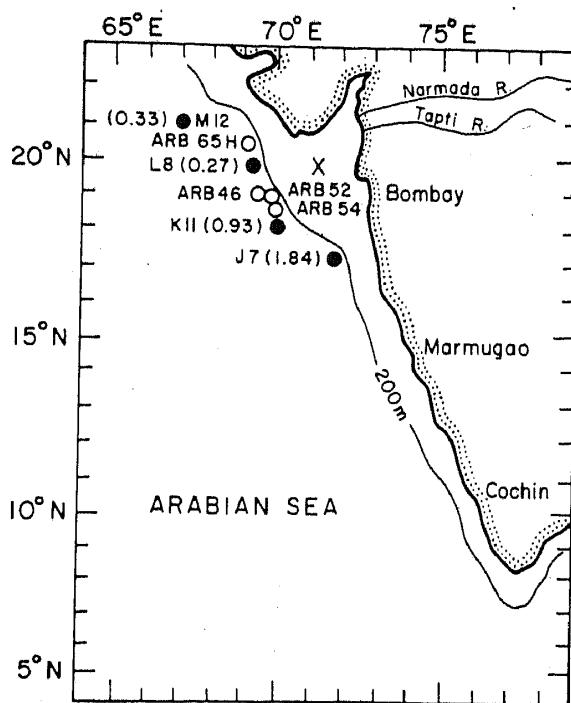
Four spade cores (size 50 × 30 × 20 cm), collected from the eastern continental margin of the Arabian Sea during the 47th cruise of the Department of Ocean Development (DOD) ship ORV Sagar Kanya, are used in this study (figure 1). Cores L8 and K11 are from 340 m water depths whereas the other two (M12 and K11), are from adjacent deeper (~2500 m) regions (figure 1). Each core, after collection, was sampled into two 2" diameter cores using plastic tubes. From one sub-core, continuous samples were collected on board the ship immediately after collection, of 1 cm thickness upto 10 cm and 2–4 cm for the rest (total length of the cores ≤ 30 cm). Samples were brought back to the laboratory for analysis. About 75% of each sample was dried at 110°C overnight, powdered and used for all investigations.

### 2.1 $\text{CaCO}_3$ and OM

The  $\text{CaCO}_3$  content was determined using the EDTA titration method to an accuracy of  $\pm 5\%$  (Barnes 1959; Yadav *et al* 1992). The OM content was determined by determining the weight loss suffered by the samples when heated at 400°C for 8–12 h.

### 2.2 U, Th, Ra and $^{210}\text{Pb}$

About 2–3 g of weighed sediment was brought into solution by HF,  $\text{HClO}_4$ , HNO<sub>3</sub> and HCl treatments in presence after addition of  $^{232}\text{U}$ – $^{228}\text{Th}$  and  $^{209}\text{Po}$  yield tracer and  $^{226}\text{Ra}$  was measured first by radon counting (Mathieu *et al* 1988). Radiochemical separation followed by electroplating of Th, U and Po ( $^{210}\text{Pb}$  was counted via its granddaughter  $^{210}\text{Po}$ ) and radio assay was carried out using standard procedures (Krishnaswami and Sarin 1976; Yadav *et al* 1992).



**Figure 1.** Map of north eastern Arabian Sea showing the core locations. Filled circles are cores used in this study, open circles represent data from Borole *et al* 1982 and x denotes a core from the continental shelf (Dilli 1986). Number in parenthesis indicates accumulation rate using  $^{210}\text{Pb}_{\text{excess}}$  method in units of mm/y. Water depths in meters at the core locations are: M12 = 2410, L8 = 340; K11 = 2640; J7 = 340; ARB65H = 343; ARB46 = 1246; ARB52 = 2240; ARB54 = 800 and X = 52 (accumulation rate = 2.5 mm/y).

### 2.3 Chemical composition

Separate aliquots of 0.5 g sediment samples were brought into solution by acid digestion as reported for U and Th isotopes. After required dilutions, these alongwith standards and blanks were used for the measurement of select trace elements viz. Al, Fe, Mn using atomic absorption spectrophotometry (Sarin *et al* 1979; Yadav *et al* 1992).

### 3. Results and discussion

Dating of all the cores is accomplished by using the method of  $^{210}\text{Pb}$  (Krishnaswami *et al* 1973; Yadav *et al* 1992).

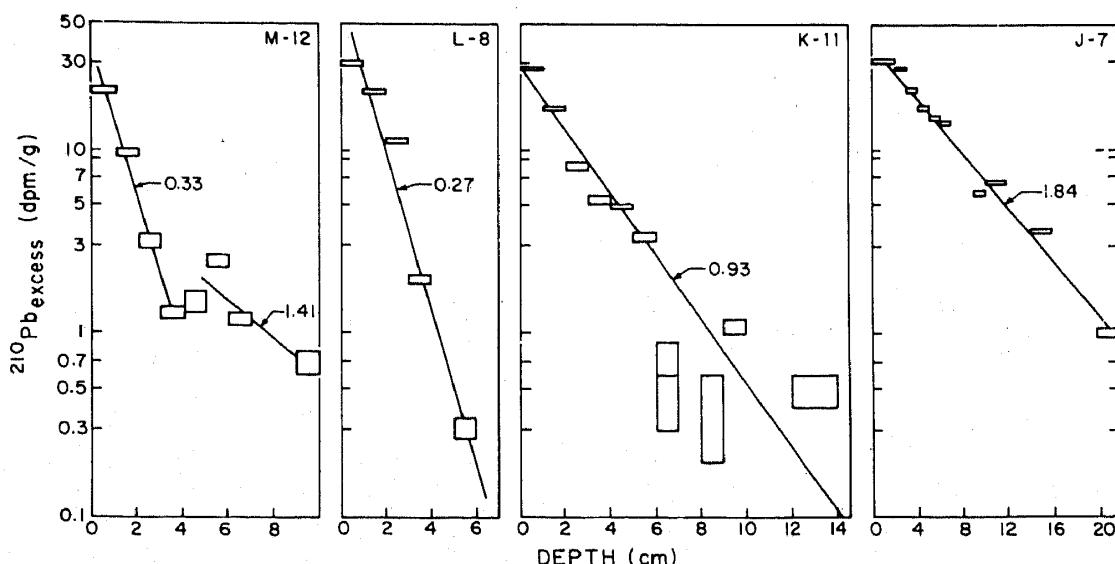
The  $^{210}\text{Pb}_{\text{total}}$ ,  $^{226}\text{Ra}$  and  $^{210}\text{Pb}_{\text{excess}}$  data are provided for cores M12 and K11 in table 1. Similar data for the two other cores L8 and J7 can be found in Yadav *et al* (1992). The total  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$  activities in all the four cores varied from 0.6 to 31.7 and 0.5 to 6.7 dpm/g respectively. In the two shallow cores, the  $^{226}\text{Ra}$  contents have been low and constant averaging  $0.6 \pm 0.1$  dpm/g. Only in the two cores M12 and K11 collected from deeper regions  $^{226}\text{Ra}$  is high, ranging from 2.7 to 6.7 dpm/g (table 1). The  $^{210}\text{Pb}_{\text{excess}}$  ranged from 0.3 to 30.9 dpm/g. The  $^{210}\text{Pb}_{\text{excess}}$  activities as a function of depth for all the four cores are plotted in figure 2. The deduced

**Table 1.**  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$  in two open ocean cores from the north eastern Arabian Sea.

Sample depth (cm)	$^{210}\text{Pb}_{\text{total}}$ (dpm/g)	$^{226}\text{Ra}$ (dpm/g)	$^{210}\text{Pb}_{\text{excess}}^*$ (dpm/g)
<u>M12</u>			
0-1	$27.3 \pm 0.6$	$5.8 \pm 0.2$	$21.5 \pm 0.6$
1-2	$16.2 \pm 0.4$	$6.5 \pm 0.1$	$9.7 \pm 0.4$
2-3	$6.5 \pm 0.2$	$3.3 \pm 0.2$	$3.2 \pm 0.3$
3-4	$4.4 \pm 0.1$	$3.1 \pm 0.1$	$1.3 \pm 0.3$
4-5	$4.7 \pm 0.1$	$3.2 \pm 0.2$	$1.5 \pm 0.2$
5-6	$6.2 \pm 0.2$	$3.7 \pm 0.1$	$2.5 \pm 0.2$
6-7	$5.2 \pm 0.1$	$4.0 \pm 0.1$	$1.2 \pm 0.1$
9-10	$4.7 \pm 0.1$	$4.0 \pm 0.1$	$0.7 \pm 0.1$
<u>K11</u>			
0-1	$32.3 \pm 0.6$	$3.9 \pm 0.2$	$28.4 \pm 0.6$
1-2	$21.9 \pm 0.5$	$4.9 \pm 0.2$	$17.0 \pm 0.5$
2-3	$13.2 \pm 0.3$	$4.9 \pm 0.2$	$8.3 \pm 0.4$
3-4	$10.6 \pm 0.2$	$5.2 \pm 0.2$	$5.4 \pm 0.3$
4-5	$10.2 \pm 0.3$	$5.3 \pm 0.2$	$4.9 \pm 0.3$
5-6	$9.2 \pm 0.2$	$5.8 \pm 0.1$	$3.4 \pm 0.2$
6-7	$7.3 \pm 0.2$	$6.7 \pm 0.2$	$0.6 \pm 0.3$
8-9	$4.5 \pm 0.1$	$4.1 \pm 0.2$	$0.4 \pm 0.2$
9-10	$4.4 \pm 0.1$	$3.3 \pm 0.1$	$1.1 \pm 0.1$
12-14	$3.2 \pm 0.1$	$2.7 \pm 0.1$	$0.5 \pm 0.1$

Errors quoted are propagated  $1\sigma$  counting statistics only

$$*^{210}\text{Pb}_{\text{excess}} = ^{210}\text{Pb}_{\text{total}} - ^{226}\text{Ra}.$$



**Figure 2.** Plot of  $\log ^{210}\text{Pb}_{\text{excess}}$  versus depth for all the four spade cores used in this study. Numbers indicated are accumulation rates in mm/y.

accumulation rates ranged from 0.27 to 1.41 mm/yr; only in the case of M12 collected from the northern most part of the Arabian Sea (21°N) is there a change in the sedimentation rate: 0.33 mm/yr for the top 4 cm below which it was faster viz. 1.41 mm/yr (figures 1 and 2).

Once the accumulation rates are determined, one can convert the depth scale to time scale provided there is no bioturbation and/or mixing during the coring operation. In general, sediments from this area especially the ones from 300–1200 m water depths are enriched in OM and one of the cores viz. L8 and some other gravity cores collected in 1992, smelled of H<sub>2</sub>S at the time of collection showing the intense anoxia prevalent in the region. Due to the extreme anoxic conditions in the two cores L8 and J7, bioturbation is not prevalent. Even in the two cores M12 and K11 from depths > 2000 m, the <sup>210</sup>Pb versus depth profiles have not indicated any bioturbation effects (figure 2). No disturbance during the coring operation is possible as the spade corer is designed to provide ~ 30 cm long undisturbed cores. Therefore, the accumulation rates obtained by the <sup>210</sup>Pb<sub>excess</sub> method have been taken to convert depth scale to time scale.

Though several elemental concentrations have been measured in the cores, we have chosen only two trace metals, Mn and U in addition to the two major elements Al and Fe. Also, CaCO<sub>3</sub> and OM which in a way indicates productivity are also measured. As one proceeds from M12 (21°N) to J7 (~ 17°N) the CaCO<sub>3</sub> content increases from 18.2% to 67.4% in the top most section (figure 3, table 3). As expected, the Fe and Al content generally varies inversely with the CaCO<sub>3</sub> content. The uranium contents of the two shallow cores are high (range = 5.68 to 9.79 ppm) compared to the two from deeper regions (1.04 to 3.92 ppm) and Mn shows, as expected, the

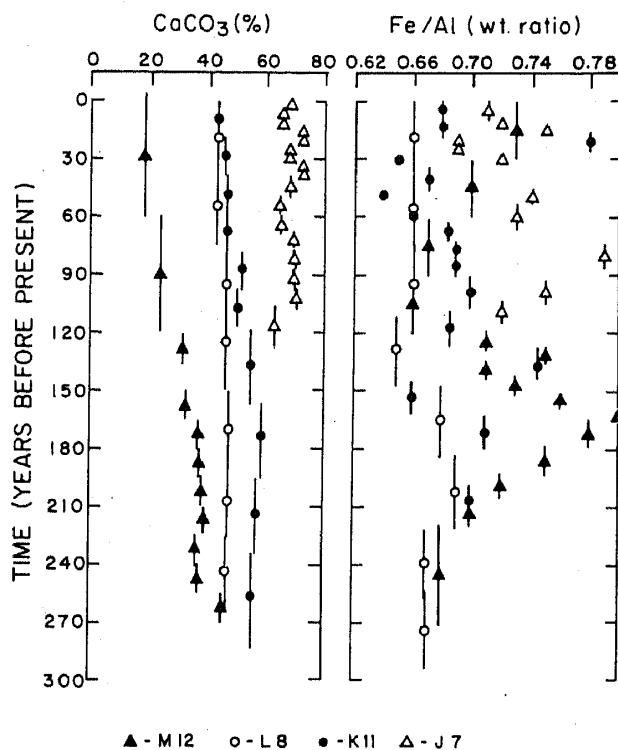


Figure 3. CaCO<sub>3</sub> and Fe/Al weight ratio as a function of time (depth).

opposite pattern. The shallow water cores which are from a reducing environment have Mn contents ranging from 99 to 198 ppm compared to the deep water ones which are more oxic and have 226 to 8312 ppm (table 2). The reducing conditions that are set up coupled with the fact that the overlying waters in this region are oxygen deficient (Naqvi *et al* 1990) as a consequence of high productivity leads to better preservation of OM. Under such conditions Mn diffuses out while uranium is removed on to the sediments from the overlying water most likely at the sediment-water interphase (Bender 1971; Anderson 1987). The near-surface-concentrations indicate the present pattern which reflects the conditions existing at the M12 and K11 core sites (figure 1) today. In oxic conditions uranium does not get removed to the sediment and manganese concentrations are either high due to its removal from water in the form of  $MnO_2$  or the detrital  $MnO_2$  contents ( $\sim 1000$  ppm) are at least preserved. For example at M12 site, the  $MnO_2$  concentrations of  $> 8000$  ppm in the top 2 sections indicate  $MnO_2$  removal from sea water whereas at K11 site, they are over 1000 ppm (table 2) quite similar to the concentrations measured in Narbada and Tapti river sediments and suspended matter (Borole *et al* 1982). Since Th (like Al) is a detrital element, the average Th/U ratio of  $\sim 4$  for average continental crustal material should be reflected in the sediments. Lower ratios indicate the presence of authigenic uranium and high ratios indicate detrital material enriched in Th relative to U. The data on five gravity cores, four from the slope and open ocean regions, and one from the shelf region (Borole *et al* 1982; Dilli 1986) are also used in the discussion here. The location of these cores are also given in figure 1.

### 3.1 Record of past variations

Now that 'time' and parameters viz. proxy chemical tracers  $CaCO_3$ , Fe and Al, Mn and U are measured, one can plot all the parameters against time in years Before Present (yBP). For a particular parameter, the variation in each of the four cores are plotted in the same figure to present a comparative picture (figures 3-5). Also metal/Al

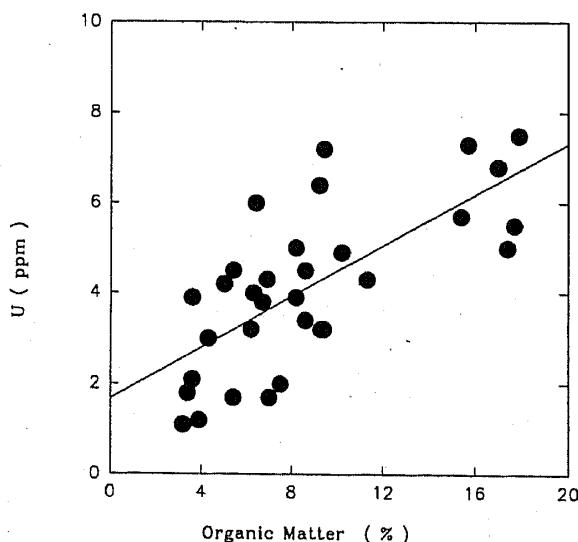


Figure 4. Uranium versus OM in all the cores indicated in figure 1. Positive correlation is noticeable. See text for discussion.

ratios are plotted instead of metal concentrations since the normalisation with respect to Al takes care of the  $\text{CaCO}_3$  and quartz (sand phases) variations as these phases do not contain any of the trace metals measured in this study.

During the past  $\sim 100$  y, there had been no appreciable change, in the  $\text{CaCO}_3$  contents ( $< 20\%$ ), but between  $\sim 100$  y and  $\sim 700$  y BP, the increase in  $\text{CaCO}_3$ , ranged from 20% to 50% (table 2, figure 3). This could imply that the productivity as represented by  $\text{CaCO}_3$  had been higher during 100–740 y BP in the region of study (see also Dilli 1986). It should be mentioned here that the  $\text{CaCO}_3$  variation at a given site depends on (i) overhead productivity, (ii) the nearbottom currents, (iii) dilution with detrital material and (iv) dissolution effects, some of which can be interrelated. Based on composition, rate of accumulation etc. it is possible to delineate the dominant parameter.

In the Narbada and Tapti estuarine suspended and bed sediments which are the main source detrital input to the region (figure 1) under study in addition to Indus river-estuarine sediments (for which data are not available), the Fe/Al ratios are uniform at  $0.9 \pm 0.2$  but tend to be relatively lower ( $0.7 \pm 0.2$ ) in the sediments of the nearby shelf and slope regions (Borole *et al.* 1982). The low Fe/Al values can, in principle, be due to the anoxic conditions prevailing in the organic rich sediments where some Fe can get reduced to  $\text{Fe}^{+2}$  form and diffuse out. All the Fe/Al ratios encountered in the sediments during the present study range from 0.63 to 0.79. The scatter is relatively larger during the past 200 y compared to the earlier period (200–740 y BP – table 2, figure 3). Relatively stronger reducing conditions could have prevailed in the sediments of this region that deposited prior to  $\sim 200$  y.

### 3.2 $U/\text{Al}$ and $\text{Th}/\text{U}$

The variation of U as a function of OM which indicates the reducing conditions prevailing in the sediments, shows a positive correlation (figure 4).

$$U = 0.28 \text{ OM} + 1.67 \quad (1)$$

( $r = 0.72$  for 32 data points)

The two deep water cores M12 and K11  $U/\text{Al} < 0.7$  and  $\text{Th}/\text{U} > 0.8$  (table 2). In contrast cores L8 and J7 have  $U/\text{Al}$  ranging from 1.6 to 4.34 and  $\text{Th}/\text{U}$  varying from 0.19 to 0.58. The  $U/\text{Al}$  ratios are plotted as a function of time in figure 5. It is evident that intense anoxic conditions and associated sulphate reduction resulting in high  $U/\text{Al}$  ratios prevailed during the past  $< 740$  y of deposition represented by these two cores L8 and J7.

The two deep water cores show low  $U/\text{Al}$  ratios ( $< 0.5$ ) for the past  $\sim 200$  y prior to which the ratios were higher (0.7–1.28). This suggests that between 740 y–200 y BP there had been high  $U/\text{Al}$  in all the cores and the region and/or its surroundings could have experienced relatively stronger reducing conditions perhaps due to high overhead productivity. Unfortunately, beyond  $\sim 300$  y the data are available in only one core viz. L8 (table 2).

### 3.2 $Mn/\text{Al}$

Another consequence of the presence of high OM and associated anoxicity in the sediments is the upward diffusion of Mn (Bender 1971). It is well known that Mn

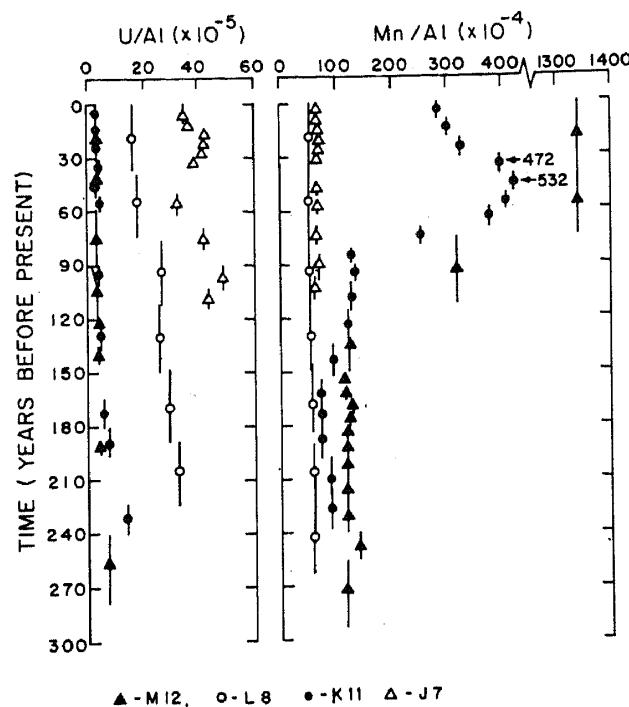


Figure 5. U/Al and Mn/Al variations versus time.

Table 2. Age,  $\text{CaCO}_3$ , Al, Fe, Mn and U concentrations in spade core sediments\*.

Sample depth (cm)	Age (yrs BP)	$\text{CaCO}_3$ (%)	Al (%)	Fe (%)	Mn (ppm)	U (ppm)	Th/U (Wt. ratio)
1	2	3	4	5	6	7	8
<u>M12</u>							
0-1	0-30	18.2	6.2	4.5	8312	$1.69 \pm 0.05$	$7.05 \pm 0.29$
1-2	31-60	18.2	6.1	4.3	8194	$1.79 \pm 0.06$	$6.18 \pm 0.28$
2-3	61-90	23.2	6.0	4.0	1897	$1.67 \pm 0.05$	$5.89 \pm 0.27$
3-4	91-120	23.2	5.9	3.9	766	$1.97 \pm 0.06$	$4.57 \pm 0.20$
4-5	121-127	27.4	5.4	3.9	659	$1.93 \pm 0.06$	$4.89 \pm 0.22$
4-5R	—	27.4	5.6	3.9	675	—	—
5-6	128-134	27.4	5.1	3.8	651	—	—
6-7	135-141	31.6	4.9	3.5	648	$1.72 \pm 0.05$	$4.12 \pm 0.17$
7-8	142-148	31.6	4.8	3.5	608	—	—
8-9	149-155	32.6	4.6	3.5	571	—	—
9-10	156-162	32.6	4.5	3.6	546	—	—
10-12	163-176	36.5	4.5	3.5	549	—	—
12-14	177-190	36.9	4.6	3.4	545	$1.84 \pm 0.05$	$3.35 \pm 0.14$
14-16	191-204	37.9	4.6	3.3	549	—	—
16-18	205-218	3.91	4.4	3.1	540	—	—
18-20	219-232	36.0	4.3	3.1	604	—	—
20-25	233-269	45.0	4.4	3.0	527	$3.02 \pm 0.08$	$1.79 \pm 0.08$
<u>L8</u>							
0-1	0-37	43.2	3.5	2.3	198	$5.68 \pm 0.17$	$0.53 \pm 0.03$
1-2	38-74	43.2	3.2	2.1	180	$5.68 \pm 0.17$	$0.58 \pm 0.03$

(Continued)

Table 2. (Continued)

Sample depth (cm)	Age (yrs BP)	CaCO <sub>3</sub> (%)	Al (%)	Fe (%)	Mn (ppm)	U (ppm)	Th/U (Wt. ratio)
1	2	3	4	5	6	7	8
2-3	75-112	46.2	2.9	1.9	163	—	—
3-4	112-148	46.2	3.0	1.9	166	—	—
2-4 <sup>+</sup>	75-148	46.2	—	—	—	7.90 ± 0.22	0.37 ± 0.02
3-4R	112-148	46.2	2.9	1.9	169	—	—
4-5	149-185	46.7	3.1	2.1	177	8.15 ± 0.27	0.37 ± 0.02
5-6	186-222	47.7	3.2	2.2	183	9.59 ± 0.27	0.27 ± 0.01
6-7	223-259	46.5	3.0	2.0	173	9.79 ± 0.20	0.33 ± 0.01
8-10	260-333	51.6	2.7	1.8	159	—	—
10-14	334-481	49.5	2.6	1.7	162	—	—
18-20	637-740	58.5	2.3	1.7	149	7.68 ± 0.25	0.28 ± 0.01
<b>K11</b>							
0-1	0-10	43.9	3.7	2.5	1068	1.04 ± 0.04	3.57 ± 0.18
1-2	11-20	49.2	3.7	2.5	1123	1.09 ± 0.84	3.41 ± 0.18
2-3	21-30	50.9	3.7	2.9	1217	1.08 ± 0.03	3.39 ± 0.17
3-4	31-40	51.2	3.26	2.4	1747	1.37 ± 0.04	3.48 ± 0.16
4-5	41-50	53.2	3.6	2.4	1915	1.23 ± 0.04	3.44 ± 0.18
5-6	51-60	51.6	3.6	2.3	1477	1.49 ± 0.04	3.16 ± 0.15
6-7	61-70	54.6	3.5	2.3	1340	—	—
7-8	71-80	54.6	3.3	2.2	845	—	—
7-8R	71-80	54.6	3.3	2.3	836	—	—
8-9	81-90	54.6	3.2	2.2	419	—	—
9-10	91-100	54.6	3.2	2.2	443	1.16 ± 0.04	3.47 ± 0.17
10-12	101-120	52.3	3.3	2.3	420	—	—
12-14	121-140	52.3	3.3	2.2	412	1.24 ± 0.04	2.96 ± 0.14
12-14R	121-140	52.3	3.3	2.3	400	—	—
14-16	141-160	—	3.2	2.4	316	—	—
16-18	161-180	56.3	3.5	2.3	251	1.78 ± 0.06	2.17 ± 0.10
18-20	181-200	59.9	3.1	2.2	226	2.14 ± 0.06	1.56 ± 0.07
20-22	201-220	59.8	3.0	2.2	254	—	—
22-24	221-240	63.5	3.0	2.1	259	3.92 ± 0.08	0.88 ± 0.04
<b>J7</b>							
0-2	0-10	67.4	1.7	1.2	108	5.96 ± 0.16	0.25 ± 0.01
2-3	11-15	65.3	1.8	1.3	118	6.66 ± 0.17	0.20 ± 0.02
3-4	16-20	65.3	1.6	1.2	99	6.97 ± 0.17	0.24 ± 0.01
4-5	21-25	71.4	1.6	1.1	103	6.89 ± 0.17	0.22 ± 0.01
5-6	26-30	71.5	1.6	1.1	102	6.67 ± 0.19	0.24 ± 0.01
6-7	31-35	67.3	1.8	1.3	114	6.83 ± 0.16	0.23 ± 0.01
9-10	46-50	72.1	1.5	1.1	101	—	—
9-10R	46-50	72.1	1.6	1.2	103	—	—
10-12	51-60	67.9	2.2	1.6	130	7.16 ± 0.16	0.25 ± 0.01
14-16	61-70	64.9	1.9	1.5	124	8.00 ± 0.21	0.22 ± 0.01
18-20	91-100	68.8	1.6	1.2	108	7.83 ± 0.19	0.19 ± 0.01
20-22	101-110	68.6	1.8	1.3	117	7.94 ± 0.22	0.21 ± 0.01

\*See figure 1 for core locations.

- Not measured.

+ Sample from a duplicate core.

R Repeat measurement.

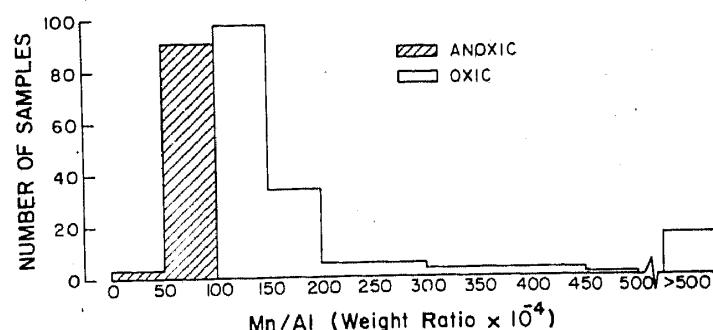


Figure 6. Histogram of Mn/Al weight ratio in sediments from the Arabian Sea, Bay of Bengal and in Narbada and Tapti estuarine suspended matter and bed sediments. A Mn/Al weight ratio of  $10^{-2}$  appears to be the demarcating value between oxic and anoxic environments.

diffuses out of marine sediments in anoxic environment and precipitates authigenically in the high oxic environments. The Mn/Al ratios of all sediments from both the Arabian Sea and the Bay of Bengal are shown as a histogram (figure 6). It appears that the Mn/Al weight ratio of  $10^{-2}$  can be taken as a boundary demarcating oxic and anoxic environments which comprise sediments derived by the weathering of the Indian subcontinent. The Narbada and Tapti estuarine particles and bed-sediments have  $\text{Mn/Al} > 10^{-2}$ . The variation of Mn/Al as a function of time in all the cores is shown in figure 5. The Mn/Al ratios have been much lower than  $10^{-2}$  ( $< 0.7 \times 10^{-2}$ ) throughout the time period represented by the two cores L8 and J7 which indicate anoxicity prevalent at the core sites, i.e. for the past  $\sim 100$  y at J7 and  $\sim 700$  y at L8 (figure 1). In the case of K11 during the period prior to about 200 y, the Mn/Al ratios were less than  $10^{-2}$  but from  $\sim 200$  BP till the present ratios increased upto  $5.3 \times 10^{-2}$  showing higher and higher oxidizing conditions which favour  $\text{MnO}_2$  precipitation. The four long gravity cores ARB46, 52, 54 and 65H all of which fall in the same region (figure 1) have all Mn/Al ratios  $< 100$  indicating anoxic conditions during the time of their deposition (Borole *et al* 1982). In the case of the northern most ( $> 21^\circ\text{N}$ —see figure 1) deep water core M12, the environment as indicated by Mn and Al ranging from  $1.2 \times 10^{-2}$  to  $13.4 \times 10^{-2}$  had been oxic throughout the time period represented by this core viz.  $\sim 7$  centuries. The Mn/Al ratio increased by over two orders of magnitude during the past  $\sim 100$  y which indicates highly oxic conditions.

### 3.3 Mn Versus U

It is indicated, in the earlier sections that Mn and U distributions in sediments cores are controlled by OM and Mn/Al ratios have been used for normalization regarding the detrital variations. In figure 7 is shown the variation of Mn versus U. The logarithm of Mn concentration gave better correlation ( $r = 0.724$  for 33 data points) against U

$$\text{Log Mn} = -0.13\text{U} + 3.083 \quad (2)$$

It appears that Mn variation is larger than that of U in samples of varying redox conditions which indicates that Mn is relatively more sensitive to even weaker reducing

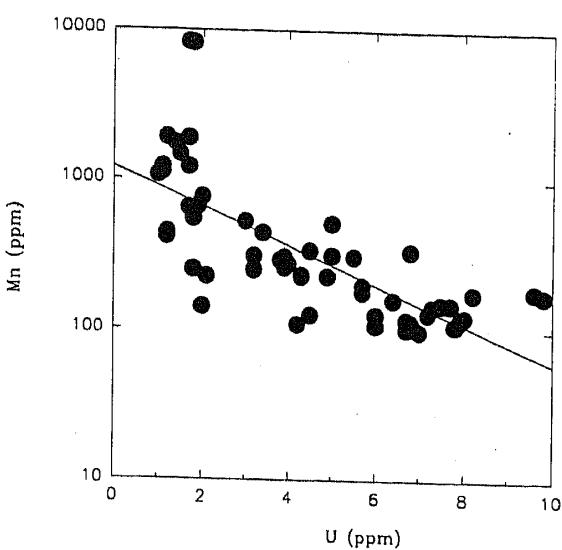


Figure 7. Long Mn versus U in cores shown in figure 1. Notice the expected negative correlation. See text for discussion.

conditions compared to U. Using equation (2) and taking a U content of  $\sim 1$  ppm for detrital sediments reaching the Arabian Sea, the Mn concentration can be deduced to  $\sim 900$  ppm which is slightly lower than  $\sim 1000$  ppm (which is the average of the material brought by the Narbada and Tapti rivers (Borole *et al* 1982).

### 3.4 Mn and Ra diffusion and its effect on sedimentation rate

In normal pelagic sediments from oxic environments, the amount of upward diffusing  $^{226}\text{Ra}$  cannot be easily ascertained due to the large amount of  $^{230}\text{Th}_{\text{excess}}$  accumulating on the top of the sedimentary column and it decays into  $^{226}\text{Ra}$  (Ku 1965). In highly anoxic areas like L8 and J7 locations, there is neither  $^{230}\text{Th}$  nor  $^{226}\text{Ra}$  ( $< 1$  dpm/g, see Yadav *et al* 1992) in excess of uranium and they are in equilibrium. As such the  $^{210}\text{Pb}_{\text{excess}}$  chronology does not get affected. However in areas of changing redox conditions like K11 (and to a small extent M12) site there is evidence (as seen by the covariance in Mn and Ra contents) to show that  $^{226}\text{Ra}$  (diffusing upwards) is scavenged down by the  $\text{MnO}_2$  precipitating out of the upward diffusing Mn (Bender 1971) in the surface layers of the sediments (tables 1 and 2). It is difficult to quantify this  $^{226}\text{Ra}$ . Since it is assumed that  $^{210}\text{Pb}$  is in equilibrium with  $^{226}\text{Ra}$  for deducing the  $^{210}\text{Pb}_{\text{excess}}$  we might have over-corrected to some extent. But this should not change the accumulation rates drastically.

## 4. Conclusions

The increasing  $\text{CaCO}_3$ , the higher U/Al and lower Mn/Al ratios in the region of study indicate that in the margin sediments at a water depth of  $\sim 300\text{--}400$  m, the environment during the past  $\sim 200$  years had been anoxic. In the cores from deeper region however, there are indications of anoxicity prior to  $> 200$  years in core K11. The northern most core M12 (figure 1) represents oxic environment throughout its

time of deposition of  $\sim$  300 years. In summary, in the north eastern Arabian Sea, the environment in the continental margin and adjacent deep water regions higher level of anoxicity prevailed upto  $\sim$  200 yrs ago. Since then, the deep water regions (depth  $\sim$  2500 m) appears to have turned oxic.

One needs to collect long undisturbed cores from gentle slope regions of the continental margins to study with high resolution the redox behaviour as it is known that high OM and uranium concentrations prevail in the margin sediments from 21°N in the Arabian Sea to the Gulf of Mannar between India and Sri Lanka (Borole *et al* 1982; Ray *et al* 1990; Paropkari *et al* 1992). High OM, U/Al and low Mn/Al values can be related to high productivity which is induced by higher upwelling rates that are a result of stronger monsoons.

### Acknowledgements

This study was supported in part by a grant from the Department of Ocean Development. We thank the Captain, crew and the scientists aboard ORV Sagar Kanya (of DOD) during its cruise No. 47, for their help. We are also thankful to Mr R R Nair, Head, Geological Oceanography Division, NIO, for providing the spade corer and help. We have been benefited by the critical review of an anonymous reviewer and are thankful to him.

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