

GEOCHEMICAL EVIDENCE OF TERRIGENOUS INFLUENCE IN DEEP-SEA SEDIMENTS UP TO 8°S IN THE CENTRAL INDIAN BASIN

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Abstract

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Thirty-two representative deep-sea sediment samples have been studied from three manganese nodule-bearing environments in the Central Indian Basin: diatomaceous–radiolarian ooze–clay, pelagic brown clay and calcareous ooze. They have been analysed for major and minor elements such as Si, Al, Ca, Mg, Na, K, Fe, Mn, P, Ti, Ba, Cu, Ni, Co, V, Zn and Cr. *R*-mode factor analysis reveals five important sources for these elements: (1) detrital (loaded with Fe, Ti, Al, Mg, Mn, P and K), (2) combined hydrogenetic–diagenetic (Mn, Ni, Cu, Co and Fe), (3) biogenic (Si), (4) sea salts (Na and Mg) and (5) dissolution residue (Ba).

Factor scores, distributional trends of detrital elements, Al, Ti and Fe concentrations and Al/Al + Fe + Mn ratios provide new geochemical evidence for the effect of the terrigenous influx from the Ganges–Brahmaputra rivers into the northern part of the basin up to 8°S which inhibits the growth of manganese nodules in this area. In contrast, incorporation of transitional metals into sediments and manganese nodules in the other two areas of the basin is governed by hydrogenetic and diagenetic processes.

Introduction

While studying the clay minerals of the deep basins on both sides of the Ninety-East Ridge, Kolla and Biscaye (1973) and Kolla (1974) observed illite-rich turbidite sediments which they interpreted as having been derived from the Ganges and Brahmaputra. Sedimentological studies by Pimm (1974) defined thin beds of terrigenous sediment in the Bengal Fan which extended as far as 8°S. Rao and Nath (1988) also studied the clay mineral distribution in the Central Indian Basin and found evidence for a Ganges–Brahmaputra riverine influx into the northern part of the basin. The present paper represents the first attempt to define the

influence of terrigenous influx into the Central Indian Ocean using sediment geochemistry as a tool. In addition, we have studied the geochemical nature of sediments from three different environments and their bearing on manganese nodule formation. *R*-mode factor analysis of the sedimentary and geochemical data has allowed conclusions regarding the sediment provenance.

Physiographic setting

The Central Indian Basin has an area of 5.7×10^6 km² and is bordered by the Ninety-East Ridge in the east, the Mid-Indian Ridge in the west and the southeastern ridge in the

south. To the north, it is open towards the Indian peninsula, while its northwest extension is bordered by the Chagos-Laccadive Ridge (Fig.1). Terrigenous, siliceous and pelagic brown clay sediments are present in the basin and calcareous sediments occur adjacent to the ridge system. Polymetallic nodules of ore

grade were recovered from this basin (Cronan, 1980; Jauhari, 1987; Sudhakar, 1988). Based on sediment composition, the basin can be divided into four areas (Fig.1). Areas 1 and 2 are in the northern and central part of the basin and are floored by siliceous sediments. Area 3 is in the southern part and is floored by pelagic brown

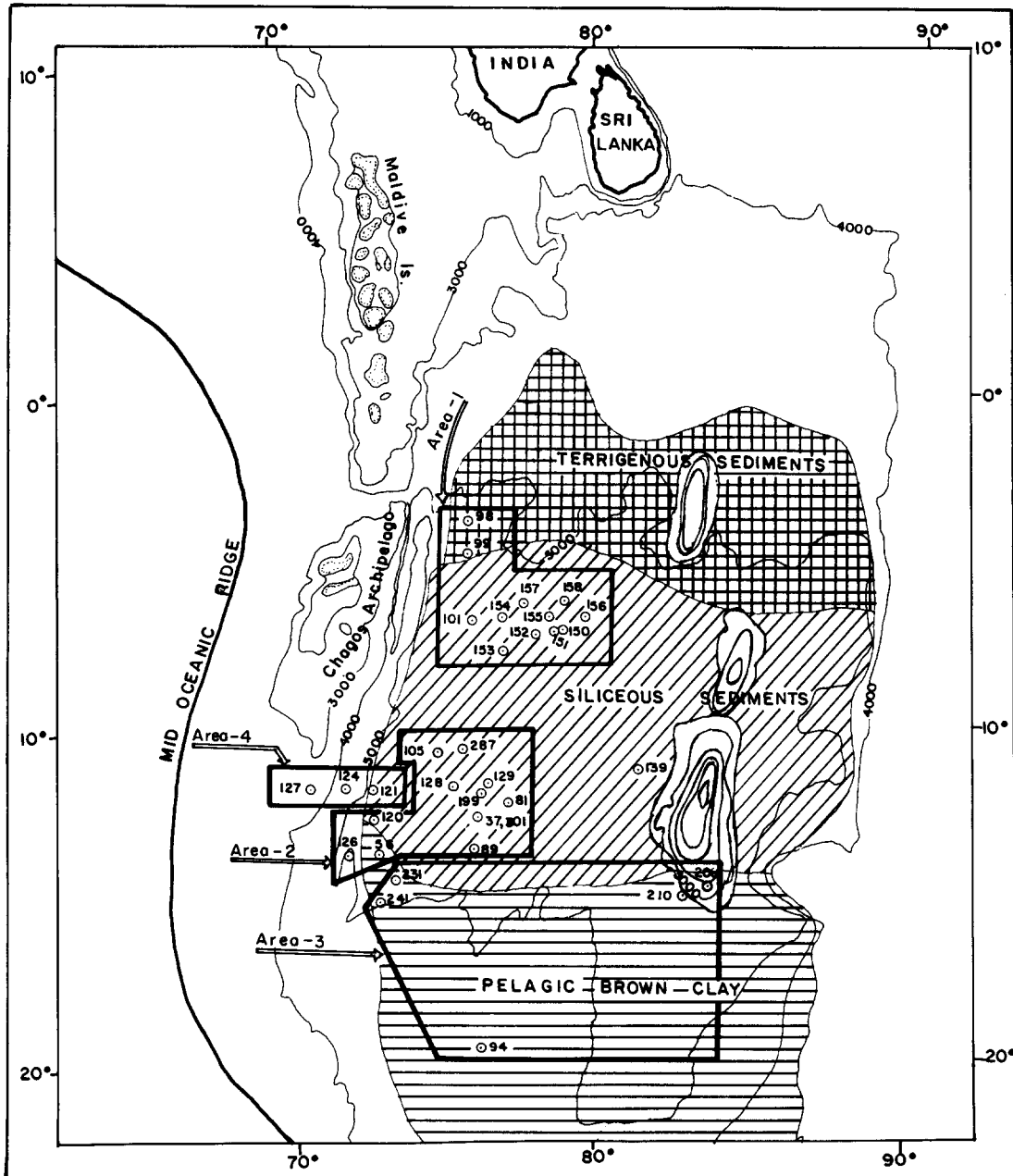


Fig.1. Sample locations and physiographic features.

clays, while area 4 is in the central western part of the basin adjacent to the Mid-Indian Ridge and is floored by calcareous sediment.

Materials

Thirty-two Petterson grab samples collected during various cruises undertaken by the National Institute of Oceanography to explore for polymetallic nodules in the Central Indian Ocean have been used in the present study.

The samples were oven-dried ($\sim 100^\circ\text{C}$), powdered in an agate mortar and analysed for major and minor elements on powdered and pressed pellets with a Philips X-ray Fluorescence Spectrophotometer. To cross-check the results the same samples were analysed with an Atomic Absorption Spectrophotometer after digesting in teflon bombs using a mixture of aqua regia and HF. The reproducibility of the elemental analysis is shown in Table 1. The analysis was cross-checked with USGS rock standards. Silicon and Al were analysed by spectrophotometry (Shapiro, 1975). Calcium carbonate was determined with the EDTA titration method (Muller, 1967).

Total seasalts were calculated following Bischoff et al. (1979a). Excess silica was calculated using the formula $\text{SiO}_2 - 3.38\text{Al}_2\text{O}_3$ where 3.38 is the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio for the

TABLE 1

Accuracy of the data (sample 37 is shown as an example)

	XRF	AAS	Rock Standard AGV 1
CaO	0.91	1.156	5.01 (4.89)
MgO	2.10	2.052	1.485 (1.49)
Na ₂ O	6.47	6.359	3.97 (4.33)
K ₂ O	2.76	2.52	2.78 (2.89)
Fe ₂ O ₃	4.65	4.346	6.873 (6.80)
MnO	0.775	0.749	0.738 (0.728)
Cu	287	291	73 (64)
Ni	227	253	NA

Rock standard AGV 1 was analysed by AAS. Values in parentheses indicate the reported values (Flanagan, 1973). Cu and Ni are represented in ppm and all other elements are percentages. NA — not analysed.

average deep-sea clay (Turekian and Wedepohl, 1961). This excess silica is considered as biogenic. Similarly, excess MgO values were computed with the factor of $\text{MgO} - 0.22\text{Al}_2\text{O}_3$ (Bischoff et al., 1979a) where 0.22 is the $\text{MgO}/\text{Al}_2\text{O}_3$ ratio for the average deep-sea clay.

The regional variation in the compositions of sediments was examined by factor analysis using the computer program developed by Fernandez and Mahadevan (1982). Columns were standardised and normalised before the data matrix preparation. The initial seven factors were rotated using the Varimax criterion.

Results and discussion

The average elemental compositions of sediments for each area, excepting those for the calcareous ooze, are given in Table 2, and the complete geochemical data is shown in Table 7. In order to understand the geochemical variations, a matrix of correlation coefficients for each area has been prepared separately (Tables 3–5). Some of the important scatter plots with linear regression curves are shown in Fig. 2.

TABLE 2

Average concentrations and factor-1 loadings for areas 1–3

Element	Area 1	Area 2	Area 3
%			
SiO ₂	55.34	59.98	47.96
Al ₂ O ₃	12.29	9.48	10.57
CaO	1.35	3.52	8.92
MgO	2.49	2.14	2.36
Na ₂ O	5.62	6.52	6.20
K ₂ O	2.49	2.14	2.16
TiO ₂	0.45	0.31	0.36
Fe ₂ O ₃	4.97	3.77	4.69
MnO	0.81	0.86	1.12
P ₂ O ₅	0.176	0.19	0.384
ppm			
Ba	3033	2479	2491
Cu	394	306	401
Ni	235	244	350
Co	76	67	105
Average loading of factor 1			
	0.1935	0.1362	0.0843

TABLE 3

Correlation matrix for area 1

	Si	Al	Ca	Mg	Na	K	Ti	Fe	Mn	P	Ba	Cu	Ni	Co
Si	1.00													
Al	0.49	1.00												
Ca	0.37	0.29	1.00											
Mg	-0.26	0.51	0.41	1.00										
Na	0.06	0.02	0.62	0.54	1.00									
K	0.89*	0.54	0.22	-0.37	-0.22	1.00								
Ti	-0.03	0.74*	0.25	0.88*	0.29	-0.98*	1.00							
Fe	0.07	0.73*	0.52	0.89*	0.44	-0.28	0.95*	1.00						
Mn	-0.14	0.21	0.35	0.73*	0.52	-0.35	0.62	0.65	1.00					
P	0.17	0.50	0.89*	0.62	0.49	0.14	0.52	0.74*	0.37	1.00				
Ba	-0.12	0.50	0.59	0.88*	0.40	-0.24	0.84*	0.92*	0.73*	0.77*	1.00			
Cu	-0.60	0.25	-0.28	0.72*	0.03	-0.62	0.69	0.52	0.56	0.01	0.55	1.00		
Ni	-0.28	0.18	0.24	0.78*	0.54	-0.47	0.65	0.65	0.65	0.32	0.71*	0.67	1.00	
Co	-0.58	-0.33	0.25	0.30	0.14	-0.55	0.15	0.23	0.23	0.33	0.49	0.28	0.49	1.00

n = 10. *Level of significance = 99%.

TABLE 4

Correlation matrix for area 2

	Si	Al	Ca	Mg	Na	K	Ti	Fe	Mn	P	Ba	Cu	Ni	Co
Si	1.00													
Al	0.37	1.00												
Ca	-0.89*	-0.47	1.00											
Mg	0.10	0.83*	-0.24	1.00										
Na	0.14	0.21	-0.25	0.10	1.00									
K	0.57	0.95*	-0.58	0.74*	0.29	1.00								
Ti	0.39	0.96*	-0.50	0.90*	0.18	0.92*	1.00							
Fe	0.34	0.97*	-0.42	0.89*	0.18	0.93*	0.99*	1.00						
Mn	0.06	0.58	-0.19	0.54	-0.12	0.44	0.51	0.52	1.00					
P	-0.07	0.78*	-0.06	0.69	0.14	0.60	0.67	0.68	0.81*	1.00				
Ba	0.47	0.19	-0.25	0.30	-0.20	0.36	0.36	0.36	-0.25	-0.32	1.00			
Cu	0.04	-0.06	-0.17	-0.31	-0.21	-0.15	-0.24	-0.25	0.47	0.27	-0.76*	1.00		
Ni	0.07	0.69	-0.20	0.52	-0.07	0.54	0.57	0.58	0.89*	0.92*	-0.41	0.55	1.00	
Co	0.05	0.70	-0.33	0.56	0.15	0.51	0.61	0.57	0.74*	0.87*	-0.48	0.50	0.89*	1.00

n = 9. *Level of significance = 99%.

Silicon and aluminium

Significant amounts of silica from land-derived aluminosilicates are added to the marine sediment. Siliceous skeletons from the water column are also important sources of silica. Aluminium is believed to be an index element for the terrigenous source. However, in the deep-sea sediments, the presence of Al is also attributed to the alteration of the ridge

rocks and hydrothermal exhalations (McMurtry and Yeh, 1981; Bonatti et al., 1983).

An attempt has been made to employ $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios (Bischoff et al., 1979a) to describe the distributional trends and the nature of the origin of the two elements. The average $\text{SiO}_2/\text{Al}_2\text{O}_3$ value is highest (6.7) in area 2, followed by area 1 (4.54) and area 3 (4.25). The excess SiO_2 varies from 4.79 to 46.45, with an average of 14.04, 27.97 and 12.27 for

TABLE 5

Correlation matrix for area 3

	Si	Al	Ca	Mg	Na	K	Ti	Fe	Mn	P	Ba	Cu	Ni	Co
Si	1.00													
Al	0.39	1.00												
Ca	0.21	-0.49	1.00											
Mg	0.06	0.77	-0.93*	1.00										
Na	0.59	0.28	-0.26	0.36	1.00									
K	0.64	0.93*	-0.38	0.68	0.59	1.00								
Ti	0.01	0.91*	-0.67	0.85	0.15	0.76	1.00							
Fe	-0.17	0.80	-0.66	0.79	0.16	0.65	0.96*	1.00						
Mn	-0.13	0.80	-0.46	0.64	0.06	0.65	0.94*	0.97*	1.00					
P	0.13	0.96*	-0.59	0.82	0.13	0.82	0.99*	0.91*	0.91*	1.00				
Ba	-0.39	-0.22	-0.50	0.26	-0.39	-0.40	-0.09	-0.17	-0.33	-0.13	1.00			
Cu	-0.85	0.14	-0.56	0.41	-0.37	-0.13	0.52	0.66	0.60	0.40	0.27	1.00		
Ni	-0.13	0.84	-0.74	0.86	-0.15	0.65	0.91*	0.99*	0.94*	0.95*	-0.48	0.63	1.00	
Co	-0.51	0.55	-0.79	0.77	-0.07	0.32	0.84	0.90*	0.82	0.75	0.19	0.89*	0.91*	1.00

n = 5. *Level of significance = 99%.

TABLE 6

Factor loading matrix after Varimax rotation

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Si	-0.07873	-0.02158	-0.09156	-0.96059	-0.14022	-0.10806
Al	-0.78306	0.21298	0.22338	0.43088	-0.01980	-0.08774
Ca	0.34484	-0.56194	-0.03678	-0.65267	0.20040	-0.10511
Mg	-0.89614	0.10771	0.17898	0.01100	-0.26856	-0.05822
Na	-0.23589	0.00215	0.10932	0.18144	-0.92682	-0.04389
K	-0.43306	0.11116	0.20525	0.70050	-0.05159	-0.17303
Ti	-0.93816	0.22989	0.09438	0.18913	-0.05749	-0.03146
Fe	-0.91156	0.09801	0.26091	0.14589	-0.14853	-0.08588
Mn	-0.51310	-0.14202	0.74914	-0.09021	-0.03947	0.08890
P	-0.43787	-0.14500	0.78964	-0.05229	-0.14037	0.04200
Ba	-0.09348	0.31735	0.02277	0.13782	-0.07620	-0.90657
Cu	0.26684	0.54297	0.57489	0.14131	0.25074	-0.24783
Ni	-0.17442	0.16679	0.90684	0.10103	-0.05533	-0.20847
Co	-0.11819	0.34320	0.84360	-0.02758	-0.10900	0.05975
V	-0.23616	0.79254	0.27408	0.13046	0.06699	-0.39219
Cr	-0.18454	0.94416	0.02407	0.00267	-0.02692	-0.16084
Percentage variance	26.03	15.937	20.926	13.706	7.059	7.461

areas 1, 2 and 3 respectively. Excess SiO_2 generally reflects the contribution of biogenic silica and quartz. Biogenic silica is most abundant in area 2. The highest Si/Al ratios and the large amounts of biogenic silica in area 2 may be due to the close proximity to the subequatorial region of high bio-

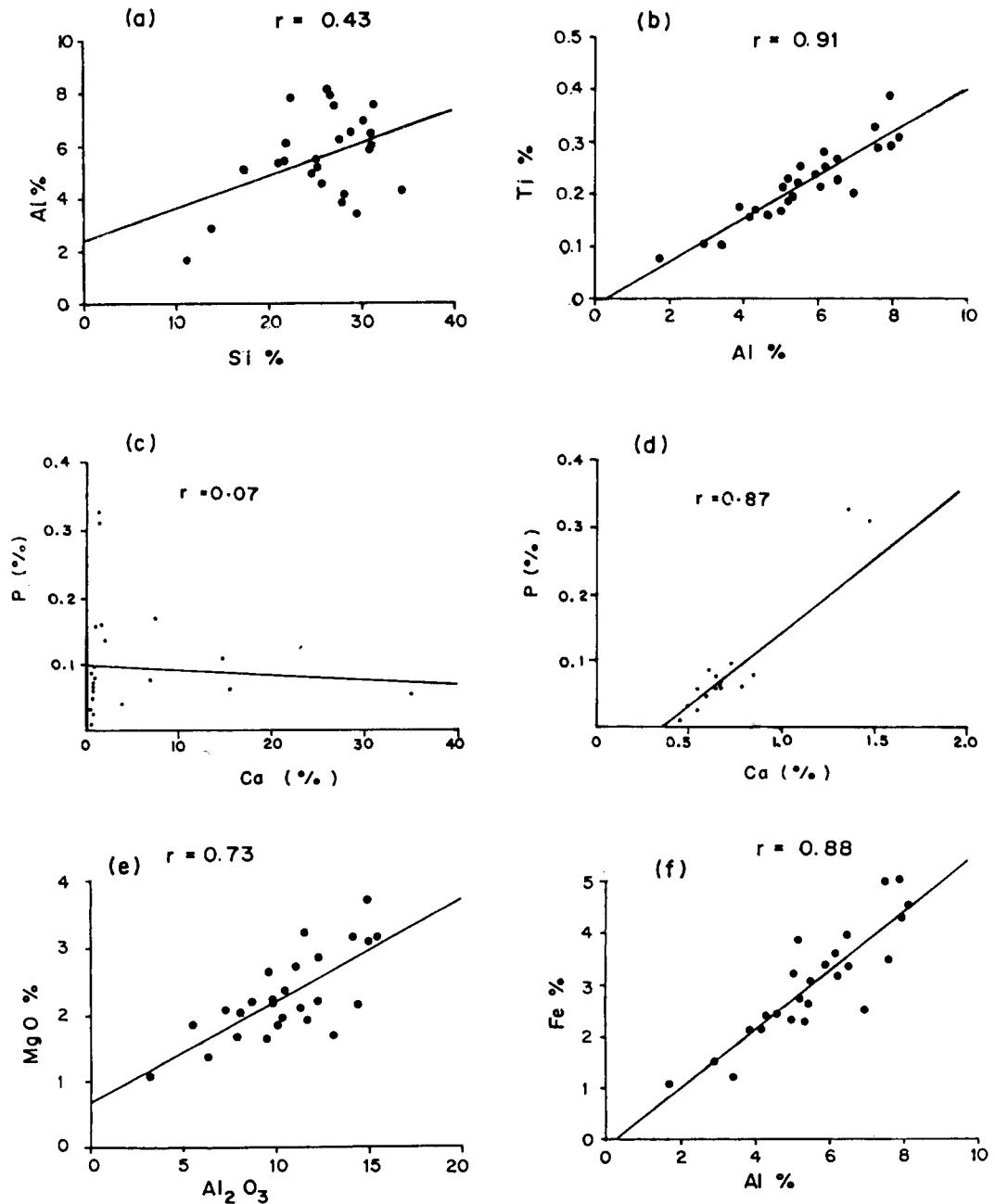
logical productivity (Parsons et al., 1977). The average $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 12.27 for area 3 may be due to the high values of two samples (206 and 231) falling in the transition zone of siliceous and pelagic brown clay regions (Table 7). These values are in good agreement with the reported values from the

same area (DeMaster (1979), and references therein).

Sodium

Sodium is released into the seawater during the weathering of continental rocks. The

sediments were not washed to remove salts since MgO , K_2O and CaO have a tendency for cation exchange and during rinsing Mg^{2+} would be substituted by Na^{2+} . The high sodium values observed for these samples are clearly due to seasalts present in the sediment or to a volcanogenic source.



Seasalts range from 3.34 to 17.94% in the study area with averages of 11.81, 14.21 and 13.34% for areas 1, 2 and 3 respectively. They have not been determined for area 4, owing to the limited number of samples.

Titanium

Titanium shows a linear relationship with Al ($r=0.91$), indicating that it is homogeneously distributed in the clay hydrolysate fraction of all the sediments (Fig.2b). Both Ti and Al are refractory elements which are extremely immobile in the marine environment (Bischoff et al., 1979b). The Ti and Al in these sediments are therefore of continental origin, although oceanic basaltic sources of Ti may be locally important (Boström et al., 1973).

The TiO/Al_2O_3 ratio decreases southward,

suggesting a reduction in the supply of terrigenous input. Area 3 has a higher average ratio than area 2, which may be attributed to weathering of Mid-Indian Ridge oceanic basalts. Further, it was found that well-mixed continental matter dominates the detrital fraction of the sediments over a wide area in this region (Schmitz, 1987).

Calcium and $CaCO_3$

The distribution of Ca in deep-sea sediments is largely regulated by biological processes and crustal minerals such as clay minerals, feldspars, etc. The CCD (carbonate compensation depth) determines the accumulation and dissolution of biogenic carbonate in the sea. The $CaCO_3$ content of areas 1 and 2 is in the range of 0.5–3%. The water depth in these areas is

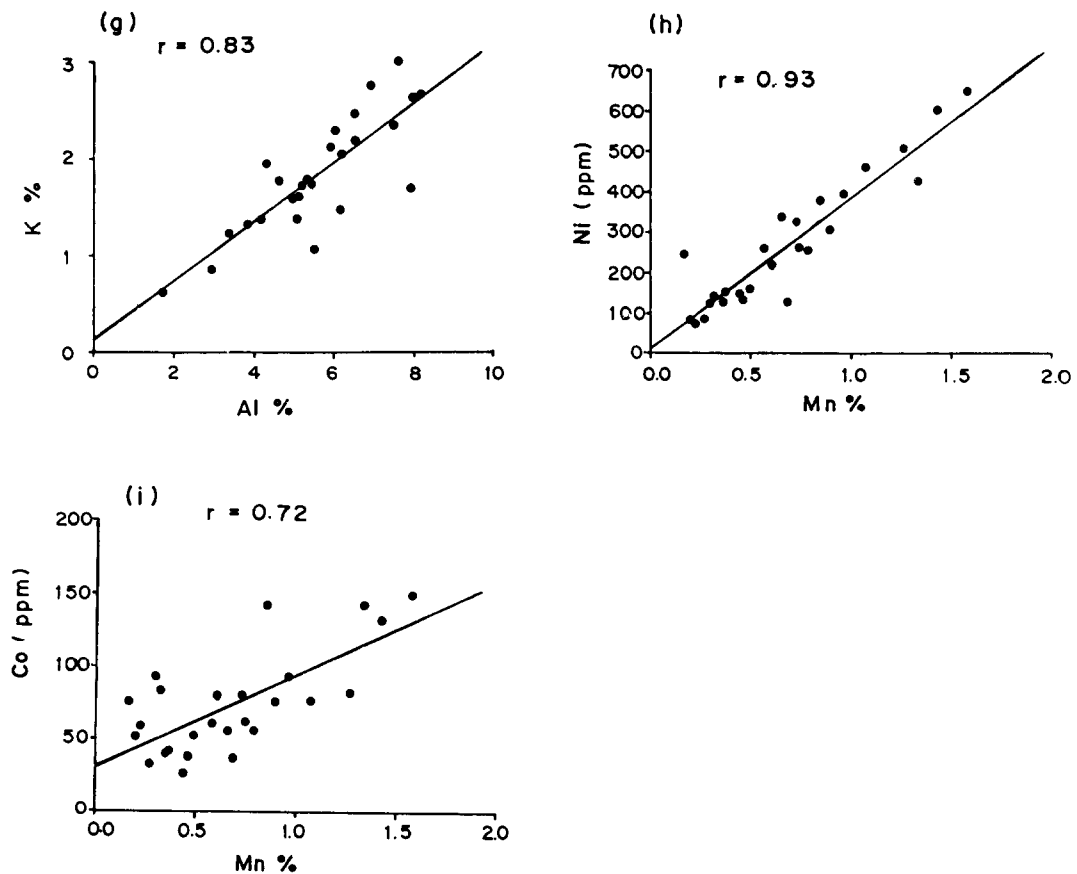


Fig.2. a-i. Important scatter plots with linear regression curves.

TABLE 7

Elemental concentrations for all samples

Station No.	%		ppm															
	CaCO ₃		Si	Al	Ca	Mg	Na	K	Ti	Fe	Mn	P	V	Cr	Ba	Cu	Ni	Co
37	1.0		31.215	6.03	0.649	1.276	4.8	2.291	0.216	3.252	0.775	0.079	73	41	2676	287	253	57
56	3.0		29.023	6.506	2.029	1.744	5.386	2.158	0.270	3.979	0.891	0.135	89	46	4725	206	308	77
206	24.0		24.748	5.018	14.821	0.990	3.279	1.577	0.168	2.293	0.682	0.109	55	23	2107	252	130	38
287	0.5		31.076	5.876	0.679	1.652	5.08	2.124	0.240	3.405	0.736	0.070	81	42	2964	278	264	63
301	NA		26.764	7.962	1.471	1.883	5.28	2.63	0.294	4.279	1.418	0.310	85	42	1989	414	601	134
124	61.5		11.240	1.678	34.999	0.6561	1.818	0.63	0.078	1.063	0.442	0.052	35	17	1848	195	149	27
126	3.0		27.109	7.481	1.621	1.932	5.14	2.324	0.330	4.983	0.961	0.162	109	65	5116	337	392	93
210	1.0		26.442	8.132	1.357	1.920	5.646	2.672	0.306	4.552	1.573	0.327	88	47	2054	409	650	152
231	11.5		25.803	4.60	6.986	1.337	6.522	1.742	0.162	2.433	0.488	0.074	61	29	2349	244	162	53
81	0.5		34.440	4.288	0.499	1.245	5.51	1.942	0.168	2.391	0.457	0.031	61	42	2983	252	130	38
157	2.0		31.318	7.597	0.793	1.312	3.88	2.97	0.288	3.503	0.356	0.061	77	55	2171	195	129	41
89	1.0		25.392	5.209	0.649	1.355	5.297	1.734	0.186	2.713	0.604	0.057	69	44	2212	383	219	81
94	14.0		17.367	5.16	7.607	1.312	4.295	1.594	0.228	3.902	1.325	0.170	94	46	1570	564	432	143
120	32.5		13.881	2.89	15.449	1.124	3.784	0.855	0.102	1.51	0.372	0.061	44	23	2037	261	148	41
128	0.5		28.005	3.86	0.457	1.264	4.295	1.328	0.174	2.119	0.217	0.009	65	47	2491	212	76	58
151	1.0		27.809	6.204	0.599	1.179	3.784	2.042	0.252	3.175	0.201	0.048	87	56	2528	277	83	53
152	1.0		25.117	5.505	0.549	1.428	4.734	1.4702	0.252	3.063	1.255	0.026	105	65	2800	457	507	84
154	1.5		21.720	5.448	0.549	1.203	2.752	1.752	0.222	2.643	0.318	0.057	124	80	2629	297	146	83
158	2.0		21.288	5.326	0.629	1.130	3.554	1.801	0.198	2.294	0.302	0.057	90	83	1906	329	124	90
241	1.0		17.539	5.06	1.071	1.598	3.242	1.378	0.216	3.231	0.844	0.157	110	84	4379	534	377	141
F-98	1.5		22.014	6.152	0.849	1.956	5.876	1.469	0.282	3.587	0.651	0.079	105	102	3010	514	342	54
F-99	2.0		22.509	7.88	0.614	2.266	3.413	1.685	0.390	4.983	1.069	0.087	136	82	5507	906	459	76
F-156	0.5		30.334	6.945	0.679	1.033	3.019	2.756	0.204	2.503	0.271	0.057	64	40	1536	193	92	33
F-199	11.5		28.267	4.171	3.849	1.015	3.383	1.369	0.156	2.161	0.039	6.905	66	33	2527	388	261	61
153	3.0		NA	NA	0.258	1.845	5.530	2.012	0.172	2.687	0.609	NA	NA	NA	NA	NA	NA	NA
101	0.5		8.862	2.096	0.486	NA	NA	NA	NA	5.379	0.914	NA	NA	NA	1567	290	306	38
129	3.0		20.142	2.271	0.449	1.614	5.842	1.219	0.112	3.001	0.310	NA	NA	NA	1456	166	97	24
150	2.0		NA	NA	0.204	1.184	4.172	2.012	0.165	2.545	0.311	NA	NA	NA	NA	NA	NA	NA
121	46.5		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
127	87.0		2.763	0.143	35.299	0.349	NA	0.012	0.037	0.189	0.046	NA	NA	NA	440	22	7	4
139	0.5		NA	NA	0.273	1.296	4.972	1.463	0.124	1.9736	0.413	NA	NA	NA	NA	NA	NA	NA

NA — not analysed.

about 5200 m and is deeper than the CCD. Area 4 samples are characterised by a high CaCO_3 content, the distribution of which is a trend of gradual reduction with increasing depth (Fig.3A). Owing to shallower depths the CaCO_3 content is high in at Stations 206 and 231 in area 3 (24 and 11.5% respectively). In the coarse fraction, dissolution features were seen as evident from the presence of foraminiferal keels (Rao, 1987).

Calcium and P show good correlation ($r=0.89$; Table 3) in area 1, while Ca alone is negatively correlated with all the elements in areas 2 and 3 (Tables 4 and 5). A regression plot of Ca versus P shows very poor correlation ($r=0.07$; Fig.2c), whereas the samples having $<2\%$ Ca show a strong positive correlation ($r=0.87$; Fig.2d) with P. This suggests that skeletal apatite is the host mineral for Ca.

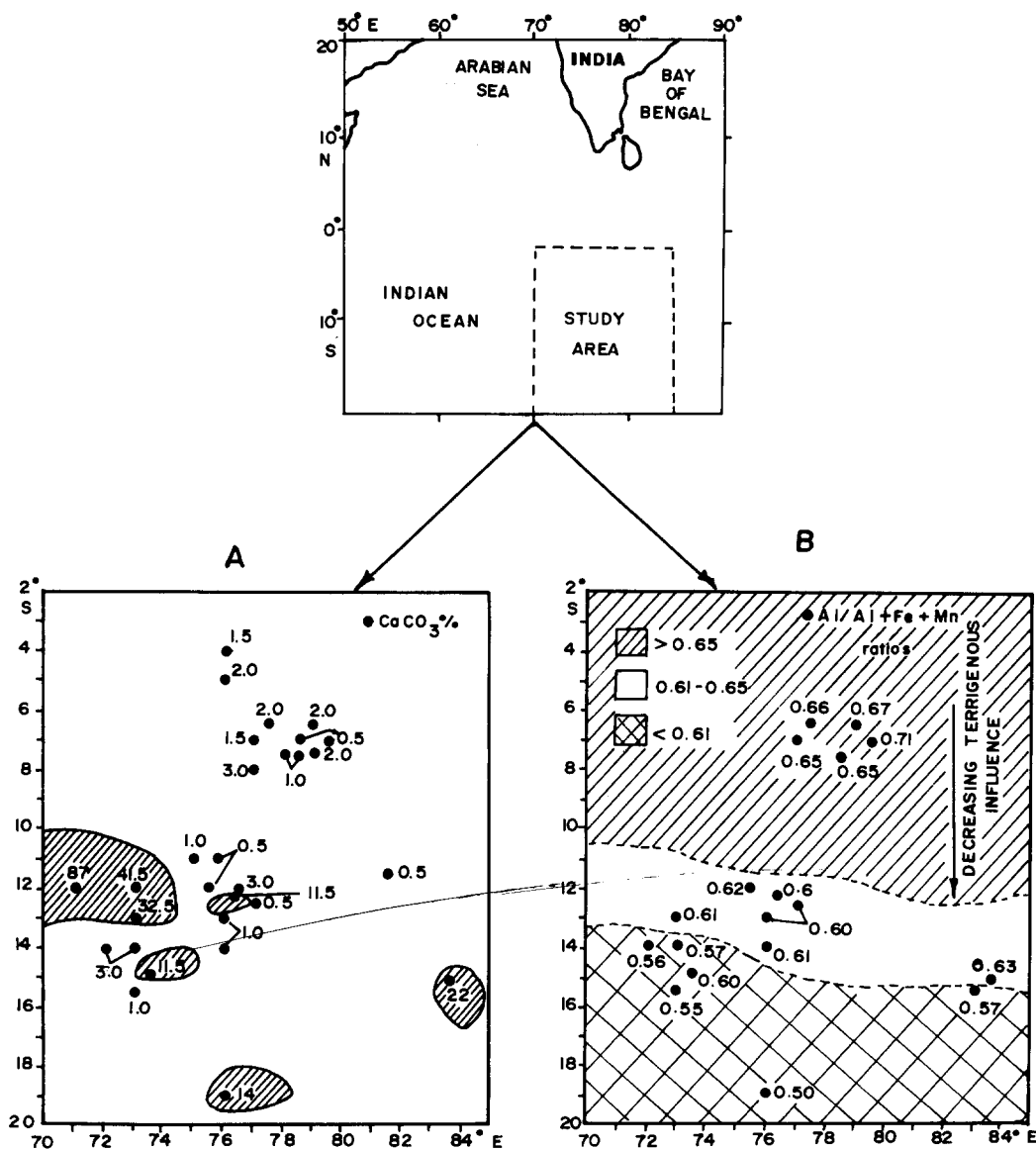


Fig.3. A. Calcium carbonate content as a percentage of surface sediments. Calcium carbonate is $>10\%$ in the shaded areas. B. $\text{Al}/(\text{Al} + \text{Fe} + \text{Mn})$ ratios of the surface sediments.

Magnesium

Good correlation is observed for MgO with Al_2O_3 ($r=0.73$; Fig.2e). The average MgO/ Al_2O_3 ratio of areas 2 and 3 is higher than for the average oceanic pelagic clay. This excess MgO has an insignificant negative correlation coefficient (-0.38) with Al_2O_3 . Nonetheless, its distribution suggests that the enrichment of MgO is greater where the continental input is lower. Of the 26 samples studied, only eleven show excess MgO ranging from 0.024 to 0.675% without any specific trend.

Low concentrations of dissolved silica in porewaters of the Pacific have been attributed to the formation of hydrated magnesium silicate — sepiolite (Bischoff and Sayles, 1972). Sepiolite coatings on silica surfaces are thermodynamically possible and indicate diagenetic maturity, but work on the nutrient chemistry of porewaters in the Central Indian Basin (Nath and Mudholkar, 1989) reveals that the dissolved silica is unsaturated with respect to sepiolite.

The distribution of montmorillonite suggests large variations in its abundance, both within the basin and within each depositional environment (Rao and Nath, 1988). Similarly, variation in the abundance of excess MgO may be related to a patchy distribution of montmorillonite.

Iron

Iron in sediments is normally fractionated between pelagic clay, hydrogenic metals and metalliferous components. Average $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratios vary from 0.4 to 0.44 in the three areas, values which are less than those of the average pelagic clays (0.58) (Turekian and Wedepohl, 1961). None of the samples has excess Fe_2O_3 . A plot of Fe versus Al (Fig.2f) indicates a good correlation ($r=0.88$). The samples from areas 2 and 3 show a much stronger relationship than the samples from area 1, which may be due to high detrital components (Al) in the northernmost two samples. A lack of excess Fe_2O_3 and a good

correlation with Al and Ti suggests that Fe is derived either from a hydrogenic source or from detrital clays.

The presence of Fe-rich montmorillonite in these samples (Rao and Nath, 1988) probably accounts for the lower Fe contents in these sediments (Dymond et al., 1973).

Potassium

Potassium is preferentially adsorbed onto clays. The presence of illite and the formation of phillipsite and other products of diagenetic reactions represents possible sinks for K (Shankar et al., 1987). In our earlier work on the sediment mineralogy of the area (Rao and Nath, 1988), high quantities of illite were found in area 1 (46–51%) compared to area 2 (35–40%) and area 3 (33–36%). The average K_2O content for these three areas is 2.49, 2.16 and 2.16% respectively, which roughly follows the trend of illite distribution.

The K versus Al graph does show a slight scatter when we consider the study area in its entirety (Fig.2g), but individual correlations for the different areas (Tables 3–5) showed excellent positive relationships for areas 2 and 3 ($r=0.93$ and 0.95). This reflects the homogeneous nature of the lithogenic material.

Factor analysis

The sum of the squares of factors 1–6 are 4.16, 2.54, 3.34, 2.19, 1.12 and 1.19 respectively. They account for about 92% of the total variance (Table 6). Examination of the factor scores shows that the first factor has higher than average Fe, Ti, Al, Mg, Mn, P and K values. This factor decreases away from the Indian Sub-Continent (Table 2). Regression plots of Ti versus Al show higher values in the southern areas than in the northern area. Although the Ti concentrations of area 1 are higher than in area 2, the $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratios decrease gradually towards the south. A strong correlation is observed between Ti and Fe for all the areas, indicating the diagenetic maturity of the sediments (Tables 3–5). The

moderate enrichment of the detrital elements Fe, Al, Ti, K and Mg and higher regression values for area 3 could be due to the effect of weathering of the adjacent ridge rocks. The Al/(Al+Fe+Mn) ratios (Boström et al., 1973) decrease with distance from the continent, together with the mineralogy and the factor scores (Fig.3B). Earlier work on the clay mineralogy (Rao and Nath, 1988) showed higher illite, kaolinite and chlorite concentrations in the northern parts of the basin and it was concluded that there is a continental influx, the source of which may be from the Ganges and Brahmaputra river discharge that has been transported by turbidity currents and subsequently deposited in the basin (Kolla and Biscaye, 1973). All these parameters allow us to designate factor 1 as a detrital or continental factor. The present work thus confirms the earlier inferences of Rao and Nath (1988) which were based on mineralogical data.

Factor 3 is dominated by Mn, Ni, Co, Cu and Fe. Regression plots of Mn with Ni ($r=0.93$) and Co ($r=0.72$) have resulted in strong positive correlations (Figs.2h and i). Nickel and Co have a better correlation in the areas 2 and 3 than in the northern part of the basin (Tables 3–5), suggesting a slower deposition together with ferromanganese oxides of hydrogenetic origin (Chester and Hughes, 1967; Moorby and Cronan, 1981). Manganese oxides are important scavengers of trace metals in the marine environment because of their unique surface properties such as large specific surface area, a high negative surface charge and a high cation adsorption capacity (Kadko et al., 1987). These properties enable Mn(IV) minerals to be extremely effective in trace metal adsorption. Thus, it is likely that the adsorptive characteristics of the upper sediment column can be appreciably altered by the redistribution and concentration of manganese oxide. It has been observed that the distribution of metals such as Ni and Co in soils and sediments are markedly influenced by their adsorption onto manganese oxides (Kadko et al. (1987) and references therein).

The experimental work of Takematsu et al.

(1984) revealed the co-precipitation of Co with manganese oxides; Co was second to Ni in the rate of precipitation. Sclater et al. (1976) related the vertical distribution of dissolved Ni in seawater to the biogeochemical cycle and found a correlation between the contents of dissolved silica and phosphate with Ni in seawater. Unlike Ni, Cu is not only contributed by the hydrogenetic source but also by the upward diffusive flux from interstitial water. Boyle et al. (1977) determined Cu distribution in oceanic waters. Their profiles have revealed a striking increase in concentrations towards the bottom. This has shown a contrasting behaviour, with silicate and phosphate supporting the diagenetic enrichment of Cu in surface sediments. The co-occurrence of these transition metals (Ni, Co and Cu) with Mn in factor 3 may be due to the combined effect of hydrogenetic and early diagenetic processes.

Factor 4 has the higher loadings for Si, K and Al, indicating a biogenic influence. As described earlier, many samples have excess silica to a maximum of 47% (sample 81). Copper and Ba have a moderate loading in this factor. Planktonic organisms such as *Acantharia* (a radiolarian) contain high concentrations of Cu in their strontium sulphate skeletons. These organisms release Cu into seawater on complete dissolution and are therefore never found in the deep-sea sediments (Greenslate et al., 1973).

Factor 5 shows a high score for Na and slight enrichment of Mg. As discussed earlier these samples were not washed free of salts, this factor possibly being the result. The presence of Mg^{2+} in this factor could be due to the fact that it replaces Na^{2+} .

Factor 6 is dominated by Ba, Cu and Ni. Barium is one of those elements incorporated into deep-sea sediments by biogenic mechanisms. It is taken up in non-skeletal material or in the soft parts of organisms which redissolve during the partial decomposition of this material while the rest is incorporated into sediments (Riley and Chester, 1971). This factor can thus be due to a dissolution residue.

Transition elements versus depth profiles in the ocean (Bruland et al., 1978) provide evidence for the relative ease of the release of Ni, Cu, Zn and Ba from decaying biogenic matter as it sinks through the water column or lies exposed on the bottom (Dymond, 1981).

Manganese nodules in the study area

The Central Indian Basin is the richest nodule-bearing area of all the basins of the Indian Ocean. The abundance and grade of these nodules varies with the environment (Mukhopadhyay, 1988). The abundance is lowest in area 1. Of the eleven stations considered, only one station has yielded nodules with a very low Mn/Fe ratio (1.03). The sediments from this area have the highest Al_2O_3 concentration (12.29%), indicating an inverse relationship with the abundance of the nodules. The grade (Ni + Cu + Co) of the nodules from this area is the lowest (0.68%) compared to areas 2 and 3 (2.5 and 1.96% respectively). The Al concentrations and the Al/Al + Fe + Mn and Ti/Al ratios in the sediments suggest that area 1 is affected by terrigenous sedimentation hindering the growth of manganese nodules in this region (Frazer and Wilson, 1980).

Unlike in the Pacific Ocean (Calvert and Price, 1977), the Central Indian Basin nodules show a considerable scatter in their Si and Al concentrations (Ahmad and Hussain, 1987), a scatter which is similar to that observed in the present study for associated sediments (Fig. 2a). This implies a significant separation of these two major elements between the nodules and the sediments.

Conclusions

(1) Decreasing contents of detrital elements such as Al, Ti, K and Fe and a decreasing ratio of Al/Al + Fe + Mn towards the south indicate that there is a terrigenous influx, apparently from the Ganges and Brahmaputra rivers, up to 8°S.

(2) The content of biogenic silica in sediments is found to be more in areas of high

biological productivity while the carbonate content is controlled by water depth.

(3) Factor analysis has revealed four important sources of supply of the various elements: detrital, combined hydrogenetic and diagenetic, biogenic, and dissolution residue.

(4) The distribution of nodules and their metal contents are poor in the northern part of the basin owing to the terrigenous influx.

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