

# Mineralogical and geochemical characters of surface sediments from the central Indian basin

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**Mineralogy and geochemistry of three types of surface sediments including their intermixtures, from 31 stations, in the ferromanganese nodule belt of the central Indian basin have been studied. Abundant illite, kaolinite and chlorite in terrigenous and siliceous sediments of the northern part of the basin indicate the influence of continental influx. This influence, however, decreases in the southern part of the basin where smectite is predominant, indicating volcanic input. The basinal sediments are enriched in trace metal (e.g. Mn, Fe, Ni, Cu, Co) inhomogeneously. Ni, Cu and Co are well correlated with Mn in terrigenous, siliceous and pelagic clay sediments. However, metal enrichment processes differ. The enrichment process is diagenetic in siliceous and, hydrogenetic in pelagic clay and terrigenous sediment-dominated domains. In terrigenous-siliceous mixed sediments, metal enrichment is a combination of hydrogenetic and early diagenetic processes. Similarity in Cu/Mn and Ni/Mn ratios between ferromanganese nodules and siliceous sediments and pelagic clay sediments, respectively, indicate that while bulk of Ni resides in the hydrogenous fraction of pelagic clay, Cu is enriched by the cumulative effect of hydrogenetic and early diagenetic processes in siliceous sediments.**

THE surface sediments of the Indian Ocean are broadly classified as (i) terrigenous, (ii) calcareous, (iii) siliceous, and (iv) pelagic clay and their intermixtures in transitional zones. Whereas the source for terrigenous sediments is predominantly continental erosion, calcareous and siliceous sediments are constituted mostly of the skeletons of micro-organisms<sup>1</sup>. In the Indian Ocean, calcareous sediments occupy the mid-Indian ridge, other ridge-systems and topographic highs, masking the influence of terrigenous input or deposition of siliceous skeletal remains. Calcite compensation depth (CCD) in the Indian Ocean varies with latitude depending on several factors<sup>2-5</sup>. Although the areal extent of terrigenous sediments in the Indian Ocean is relatively limited, the enormous thickness of these sediments<sup>6</sup> however accounts for more than 70% of the total sediment.

Terrigenous sediments occupy mainly the northern part of the central Indian basin (CIB) down to about 5°S in the western margin and about 6.5°S in the eastern

margin<sup>7</sup>. Clay mineral distribution in the surface sediments of the CIB indicates that the terrigenous influence in this basin extends to 8°S (ref. 8). Terrigenous sediment is replaced southward by the siliceous type that extends to about 13°S in the western part and 15°S in the eastern part of this basin<sup>7</sup>. This is followed southward by pelagic clay extending from the pelagic clay-siliceous mixed sediment zone up close to the southern extremity of this basin at around 27°S (ref. 7). Earlier studies on the distribution, chemical composition and mineralogy of the sediments had provided insights regarding the paleoceanographic processes operative in different parts of the Indian Ocean including the CIB<sup>9-17</sup>. However, these investigations were not aimed at establishing any correlation between the nature and distribution of manganese nodules and their host sediment substrates of this basin. Cronan and Tooms<sup>18</sup>, Rao and Nath<sup>8</sup> and Nath *et al.*<sup>17</sup> provided some basic information pertaining to the association of different sediment types with nodules in the CIB, though no specific genetic relationship between nodules and sediments could be established.

An attempt has been made in the present work to characterize the sediments (each sediment type separately and also as a whole) collected from a large part of the CIB, in terms of their chemistry and mineralogy and to establish the relationship between the composition of sediments and of the associated ferromanganese nodules. Surface sediment samples from 31 locations have been chosen (Figure 1, Table 1). These include, 13 samples from siliceous, 5 from terrigenous, 2 each from mixed siliceous-terrigenous and mixed siliceous-pelagic clay, 6 from pelagic clay and 3 from mixed terrigenous-calcareous sediment-dominated domains. These samples were collected during several cruises organized primarily for the exploration of manganese nodules and so, the sample distribution pattern in Figure 1 shows some irregular distribution.

## Methodology

The sediment samples were collected using a Petterson grab. After noting their colour, smear slides were examined microscopically. The samples were washed with de-ionized water before drying and powdering. The

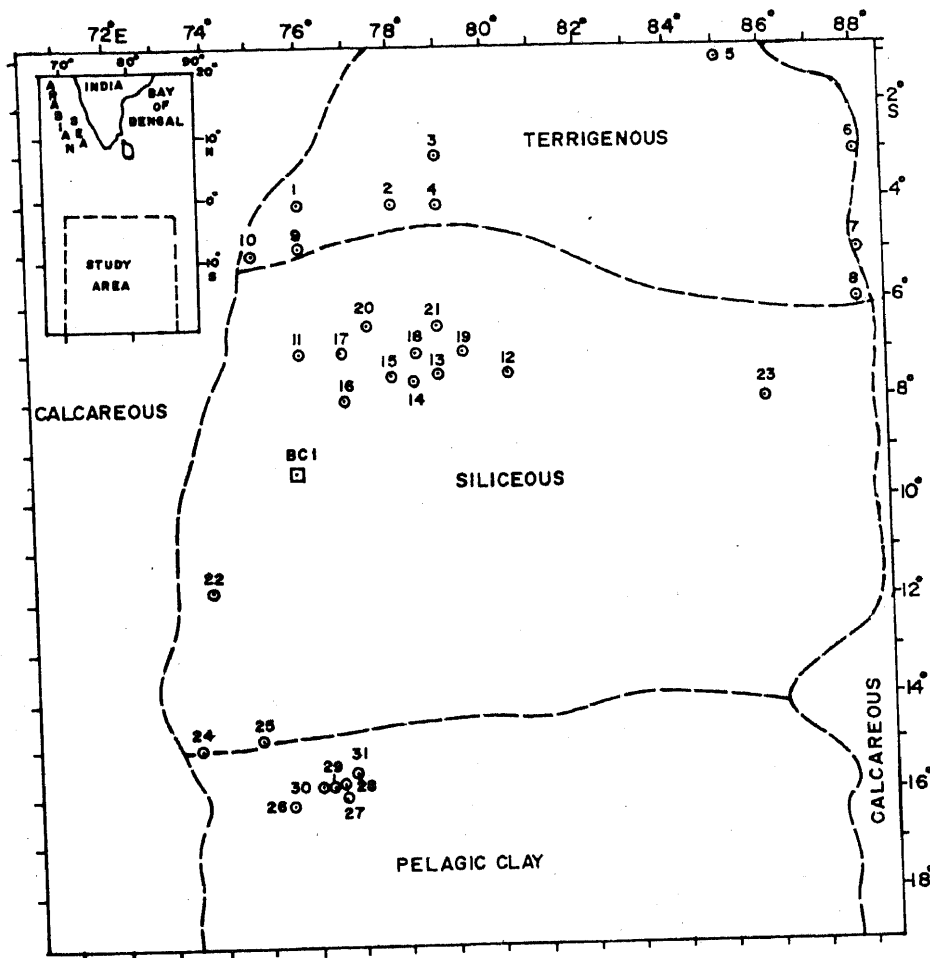


Figure 1. Sediment sampling locations in the central Indian basin. BC1 is the box core location. The dotted lines are approximate boundary between adjacent sediment types (ref. 7).

powdered, digested samples were analysed for Mn, Fe, Ni, Cu, and Co along with USGS rock standards AGV-1 and BCR-1 using an atomic absorption spectrophotometer (Perkin-Elmer, PE-5000). The accuracy of the chemical analyses was  $\pm 5\%$ . Mineralogy of the dried and powdered ( $-230$  mesh) samples was determined by X-ray diffractometry (Philips, PW 1130) with a nickel filtered  $\text{CuK}\alpha$  target. The scanning range of  $2\theta$  angles was from  $8^\circ$  to  $31^\circ$ . The scanning speed was kept at  $2^\circ$   $2\theta$  per minute. The total organic carbon of the samples was determined by the wet oxidation method following Wakeel and Riley<sup>19</sup>. Internal sediment standards were used to check the accuracy of the analyses and were found to be accurate within 5%. In order to understand the geochemical variations in these sediments (Table 1), correlation matrix of the elements for different sediment domains were prepared (Tables 2 a-d). Scatter plots for all sediment samples are shown in Figures 2 a-g. The regional variation in the compositions of sediments was examined by  $Q$  mode factor analysis using the computer

program developed by Fernandez and Mahadevan<sup>20</sup>. Columns were standardized and normalized before data matrix preparation. The initial seven factors were rotated using the Varimax method.

## Results and discussion

The samples studied have shades of yellowish brown and reddish brown indicating differences in their mineralogical and chemical characteristics. Smear slides of some of the sediment samples show the presence of a few fine grains of volcanogenic components, e.g. fragments of glass, feldspar, pyroxene, olivine, etc. Some of these components are fresh, indicating their derivation from a nearby provenance<sup>21</sup> and also possibly their young age. Whereas illite is abundant in terrigenous and siliceous sediments and impoverished in pelagic clays, smectite exhibits the opposite trend. Kaolinite + chlorite is present in all types of sediments without any specific trend of enrichment except in the

Table 1. Geochemical data and related details of surface sediment samples from the Central Indian basin

Station no.	Lat.°S	Long.°E	Depth (m)	Sediment type	Mn (%)	Fe (%)	Ni (%)	Cu (%)	Co (%)	Cu/Ni	Mn/Fe	Cu/Mn	Ni/Mn	Co/Mn
1	4°02.52'	76°01.56'	4869	T	0.64	3.69	0.019	0.026	0.005	1.37	0.17	0.041	0.030	0.008
2	4°00.00'	78°00.00'	4900	T	0.70	4.94	0.019	0.029	0.005	1.52	0.14	0.041	0.027	0.007
3	3°00.00'	79°00.00'	4980	T	0.65	4.35	0.017	0.024	0.004	1.42	0.15	0.037	0.026	0.006
4	4°00.00'	79°00.00'	4580	T	0.46	4.39	0.014	0.023	0.004	1.67	0.11	0.050	0.030	0.009
5	0°59.88'	85°00.78'	4620	T	0.24	2.82	0.008	0.012	0.002	1.48	0.09	0.050	0.033	0.008
6	2°58.62'	87°59.28'	4860	TC	0.34	3.00	0.009	0.016	0.003	1.70	0.11	0.047	0.027	0.009
7	5°00.72'	88°00.72'	5040	TC	0.29	2.24	0.007	0.013	0.002	1.91	0.13	0.045	0.024	0.007
8	6°01.98'	88°02.82'	5160	TC	0.25	2.48	0.006	0.011	0.003	1.97	0.10	0.044	0.024	0.012
9	5°00.00'	75°59.52'	4492	TS	1.45	5.36	0.029	0.059	0.003	2.04	0.27	0.041	0.020	0.002
10	5°00.00'	75°00.00'	5400	TS	0.80	3.10	0.016	0.027	0.005	1.66	0.26	0.034	0.020	0.006
11	7°00.54'	75°59.94'	5290	S	0.18	3.06	0.007	0.016	0.003	2.25	0.06	0.089	0.039	0.017
12	7°29.64'	80°29.64'	5200	S	0.48	2.78	0.007	0.019	0.003	2.76	0.17	0.040	0.015	0.006
13	7°26.64'	78°57.24'	5175	S	0.28	2.50	0.006	0.012	0.003	1.97	0.11	0.043	0.021	0.011
14	7°33.00'	78°28.02'	5200	S	0.16	2.66	0.006	0.018	0.003	3.14	0.06	0.113	0.038	0.019
15	7°29.34'	78°00.84'	5175	S	1.23	2.80	0.028	0.026	0.005	0.94	0.44	0.021	0.023	0.040
16	8°01.44'	76°58.02'	5200	S	0.53	2.90	0.014	0.025	0.005	1.80	0.18	0.047	0.026	0.094
17	7°00.78'	76°55.74'	5275	S	0.45	3.32	0.010	0.021	0.004	1.91	0.14	0.047	0.022	0.088
18	7°00.24'	78°29.70'	5180	S	0.55	3.75	0.015	0.028	0.005	1.83	0.15	0.051	0.027	0.090
19	7°04.02'	79°30.00'	5200	S	0.20	2.03	0.006	0.010	0.002	1.71	0.10	0.050	0.030	0.010
20	6°28.08'	77°26.34'	5250	S	0.28	2.66	0.008	0.014	0.003	1.87	0.11	0.050	0.029	0.011
21	6°30.36'	78°56.70'	5250	S	0.33	2.66	0.009	0.015	0.003	1.74	0.12	0.046	0.027	0.091
22	11°44.63'	73°59.68'	4896	S	0.44	1.08	0.016	0.017	0.003	1.07	0.41	0.039	0.036	0.068
23	8°00.60'	86°01.56'	5220	S	0.16	2.26	0.005	0.011	0.003	2.19	0.07	0.069	0.031	0.019
24	14°59.78'	73°44.56'	5161	SP	0.60	1.52	0.021	0.020	0.007	0.93	0.40	0.033	0.035	0.012
25	14°47.38'	74°59.30'	5055	SP	0.42	1.53	0.014	0.020	0.007	1.42	0.28	0.048	0.033	0.017
26	16°06.90'	75°37.38'	4993	S	0.82	1.51	0.026	0.023	0.009	0.89	0.54	0.028	0.032	0.011
27	15°59.78'	73°44.56'	5025	P	0.40	1.23	0.013	0.015	0.004	1.09	0.33	0.038	0.033	0.010
28	15°44.95'	76°42.73'	5074	P	0.44	1.22	0.015	0.014	0.004	1.09	0.36	0.032	0.034	0.091
29	15°44.77'	76°29.81'	4969	P	0.40	1.20	0.013	0.014	0.004	1.06	0.33	0.035	0.033	0.010
30	15°44.67'	76°14.48'	5008	P	0.41	1.12	0.014	0.014	0.004	1.02	0.37	0.034	0.034	0.098
31	15°29.53'	76°59.67'	5010	P	0.40	1.14	0.014	0.013	0.005	0.97	0.35	0.033	0.035	0.013
BC1	9°30.98'	75°57.92'	5310	S	0.62	3.33	0.017	0.070	0.007	4.12	0.19	0.113	0.027	0.011

T, Terrigenous; C, Calcareous; S, Siliceous; P, Pelagic clay; BC1, Box core; TC, Terrigenous-calcareous mixture; TS, Terrigenous-siliceous mixture; SP, Siliceous-pelagic clay mixture.

Table 2a. Correlation matrix for terrigenous sediments ( $n = 5$ )

	Mn	Fe	Ni	Cu	Co	Mn/Fe	Cu/Ni	Ni + Cu + Co	Depth
Mn	1.0000								
Fe	0.7801	1.0000							
Ni	<b>0.9785</b>	0.7124	1.0000						
Cu	<b>0.9489</b>	0.8540	<b>0.9626</b>	1.0000					
Co	<b>0.9827</b>	0.8371	<b>0.9761</b>	<b>0.9848</b>	1.0000				
Mn/Fe	0.8835	0.4146	0.9129	0.7767	0.8156	1.0000			
Cu/Ni	-0.3016	0.3286	-0.3163	-0.0504	-0.1715	-0.6221	1.0000		
Ni+Cu+Co	<b>0.9820</b>	0.7794	<b>0.9685</b>	<b>0.9495</b>	<b>0.9596</b>	0.8885	-0.2373	1.0000	
Depth	0.8428	0.4554	0.7748	0.6365	0.7536	0.8360	-0.6783	0.7726	1.0000

All bold typed values are significant at 99.9% confidence level.

Table 2b. Correlation matrix for siliceous sediments ( $n = 14$ )

	Mn	Fe	Ni	Cu	Co	Mn/Fe	Cu/Ni	Ni + Cu + Co	Depth
Mn	1.0000								
Fe	0.2335	1.0000							
Ni	<b>0.9397</b>	0.1086	1.0000						
Cu	<b>0.7466</b>	0.5699	<b>0.7563</b>	1.0000					
Co	<b>0.8261</b>	0.6206	<b>0.7799</b>	<b>0.9146</b>	1.0000				
Mn/Fe	<b>0.8182</b>	-0.2990	<b>0.8758</b>	0.4949	0.4803	1.0000			
Cu/Ni	-0.6192	0.2380	-0.7340	-0.2555	-0.3987	-0.7566	1.0000		
Ni+Cu+Co	<b>0.8788</b>	0.3690	<b>0.9293</b>	<b>0.9023</b>	<b>0.8455</b>	<b>0.7359</b>	-0.5491	1.0000	
Depth	-0.3108	0.4816	-0.4009	-0.1438	-0.0707	-0.6845	0.5067	-0.3507	1.0000

All bold typed values are significant at 99.9% confidence level.

Table 2c. Correlation matrix for pelagic clay sediments ( $n = 6$ )

	Mn	Fe	Ni	Cu	Co	Mn/Fe	Cu/Ni	Ni + Cu + Co	Depth
Mn	1.0000								
Fe	<b>0.9536</b>	1.0000							
Ni	<b>0.9991</b>	<b>0.9459</b>	1.0000						
Cu	<b>0.9910</b>	<b>0.9670</b>	<b>0.9887</b>	1.0000					
Co	<b>0.9892</b>	<b>0.9442</b>	<b>0.9905</b>	<b>0.9783</b>	1.0000				
Mn/Fe	<b>0.9860</b>	0.8922	<b>0.9898</b>	<b>0.9687</b>	<b>0.9726</b>	1.0000			
Cu/Ni	-0.7853	-0.6111	-0.7952	-0.7357	-0.8311	-0.8345	1.0000		
Ni+Cu+Co	<b>0.9957</b>	0.9500	<b>0.9940</b>	<b>0.9909</b>	<b>0.9934</b>	<b>0.9798</b>	-0.8114	1.0000	
Depth	-0.2051	-0.1638	-0.1821	-0.2343	-0.2343	-0.1897	0.4402	-0.2798	1.0000

All bold typed values are significant at 99.9% confidence level.

Table 2d. Correlation matrix for mixed terrigenous-calcareous sediments ( $n = 3$ )

	Mn	Fe	Ni	Cu	Co	Mn/Fe	Cu/Ni	Ni + Cu + Co	Depth
Mn	1.0000								
Fe	0.7154	1.0000							
Ni	<b>0.9946</b>	0.7842	1.0000						
Cu	<b>0.9993</b>	0.6894	<b>0.9901</b>	1.0000					
Co	-0.2662	0.4831	-0.1645	-0.3012	1.0000				
Mn/Fe	0.2662	-0.4831	0.1645	0.3012	-1.0000	1.0000			
Cu/Ni	-0.9698	-0.8642	-0.9899	-0.9603	0.0231	-0.0231	1.0000		
Ni+Cu+Co	0.8963	0.9511	0.9375	0.8794	0.1890	-0.1890	-0.9724	1.0000	
Depth	-0.9987	-0.7501	-0.9986	-0.9962	0.2168	-0.2168	0.9810	-0.9177	1.0000

All bold typed values are significant at 99.9% confidence level.

northern part of the basin. Quartz and feldspar are ubiquitous.

The presence of illite and kaolinite + chlorite in terrigenous and siliceous sediment domains in the northern part of the basin and their gradual decrease towards the

pelagic clay domain may indicate the higher influence of continental detritus in the northern part of CIB<sup>17,22</sup>. This continental detritus might have been contributed by the Ganges and Brahmaputra, transported to the CIB by turbidity currents<sup>5,8,9,15</sup>.

The higher concentration of smectite in pelagic clay is probably related in part to the high input of volcanic materials from the mid-Indian Ocean ridge and the Ninety East ridge systems<sup>10</sup>. In addition, several seamounts present in this basin could also be a potential source<sup>23</sup>.

In general, in CIB sediments good correlation exists between Mn and Ni ( $r = 0.92$ , Figure 2a) than between Mn and Cu ( $r = 0.67$ , Figure 2b) and Mn and Co ( $r = 0.67$ , Figure 2c). However, in specific sediment types, e.g. terrigenous, siliceous, pelagic clay and terrigenous-calcareous mixed sediments (Tables 2c-e) the correlation of Mn with Ni is slightly better ( $r = 0.94$  to  $0.99$ ). Good correlations also exist between Mn and Cu in terrigenous and siliceous sediments ( $r = 0.95$  and  $r = 0.75$ , respectively, Tables 2a, b). Co shows strong positive correlation with Mn in terrigenous ( $r = 0.98$ ) and pelagic clay ( $r = 0.99$ ) sediments, while it is less significant in siliceous sediments ( $r = 0.83$ ). The pelagic clay-siliceous mixed sediments show very poor correlations of Mn with Cu and Co. Therefore Ni, Cu and Co are well correlated with Mn in terrigenous, siliceous and pelagic clay sediments, and weakly correlated with Mn in siliceous-pelagic clay and siliceous-terrigenous mixed sediments.

Incorporation of Ni and Co in the Mn phase of deep-sea sediments could be due to intimate intergrowth of Ni and Co with Mn oxides or by solid solution of both elements within Mn oxide phases<sup>24</sup>. Ni and Co exhibit a better correlation with each other in terrigenous and pelagic clay sediments than in the siliceous sediments, probably suggesting their deposition together with particulate ferromanganese oxides of hydrogenetic origin<sup>17,25,26</sup>. Manganese oxides are important scavengers of trace metals in the marine environment because of the following reasons, e.g. (i) high negative surface charge, (ii) high cation adsorption capacity and (iii) large specific surface area<sup>27</sup>. Thus, the trace metal concentration in the surface sediments is at least partially dependent on the abundance of manganese oxides. However, in the case of biogenic sediments (siliceous and calcareous oozes) some or most of the organisms could additionally scavenge these trace metals from sea water during their life-time and contribute them to the sediments<sup>28-30</sup>.

The distribution of Ni in the water column was correlated to the oceanic biogeochemical cycle by Sclater *et al.*<sup>31</sup>. They also indicated the correlation of Ni with the dissolved silica and phosphate contents in sea water. The process of co-precipitation of cobalt with manganese oxides was studied in the laboratory by Takematsu *et al.*<sup>32</sup>. They also found that Ni precipitated earlier than Co.

The phenomenon of increase in dissolved Cu concentrations with the increase in water depth was indicated by Boyle *et al.*<sup>33</sup>. Their observation was in contrast to the distribution pattern of silicate and phosphate in the water column<sup>31</sup>. The enrichment of Cu in the bottom

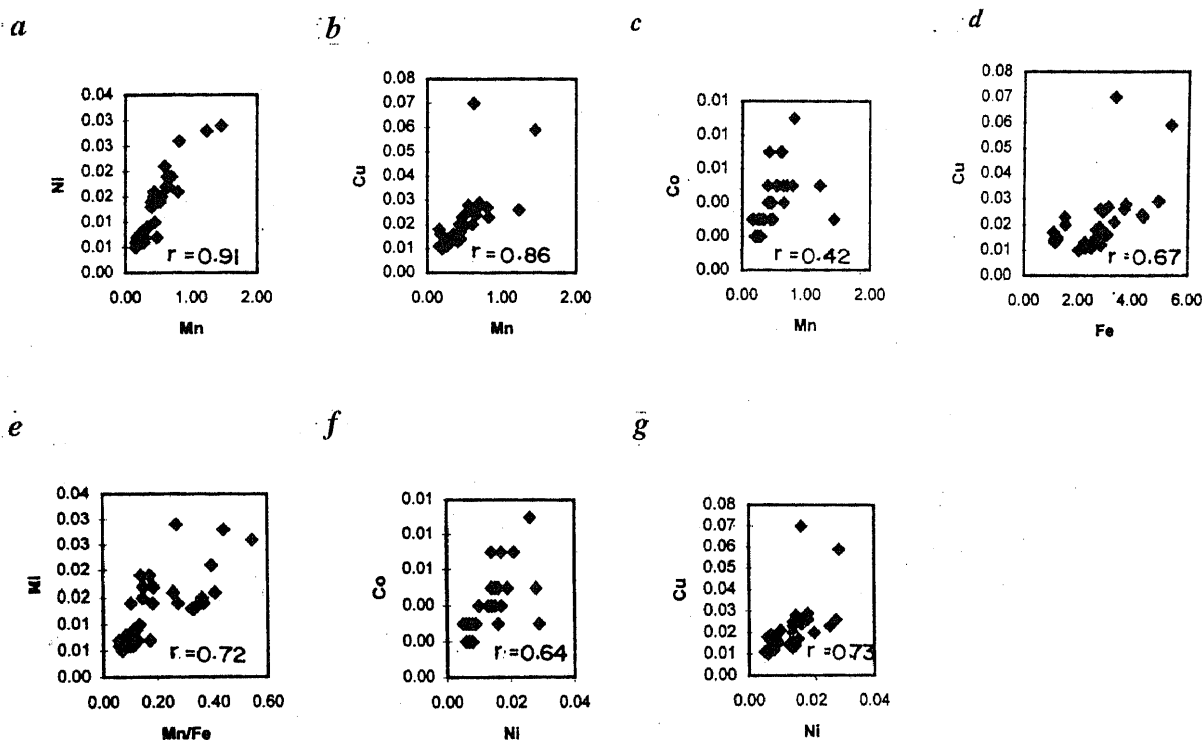
sediments observed here may be either from basinal water below the lysocline or from the biogenic components of the sediments that liberated to the pore waters during diagenesis, which subsequently migrated to the surface sediments.

The concentration of total organic carbon measured in these surface sediments ranges between 0.48% and 1.20% (mean 0.75%). Burial of this organic matter and development of subsequent suboxic condition may enhance the mobility of trace metals through sediment pore water to the upper oxygenated condition at the sediment water interface where subsequent reprecipitation of the trace metals takes place in suitable Eh-pH conditions.

The good correlations of Ni, Cu and Co with Mn, in specific sediment facies (Tables 2a-d), although in variable extent, possibly indicates variation in the incorporation of Ni, Cu and Co in the Mn oxide phases in those sediments. This incorporation process could be due to the combined effects of hydrogenesis and early diagenesis.

The variable concentration of Ni, Cu and Co with respect to Mn has been compared in different sediment types. The calculated ratios of Cu/Mn and Ni/Mn are less than one (Table 1), and this probably indicates the retention of Mn in the solid phase of the highly oxidized surface sediments<sup>34-36</sup>. While siliceous sediments show highest Cu/Mn (0.11) and Ni/Mn (0.039) values, the pelagic clay sediments show highest Co/Mn values (0.098), which probably indicates different degrees of Mn retention and hence variable effects of diagenesis on the enrichment of trace metals in these sediments. The differences in the ratios of Cu/Mn and Ni/Mn in siliceous sediments also supports the idea that Cu and Ni are not associated in same degree with the Mn oxide phase in this sediment. The lowest values of Cu/Mn (0.02), Ni/Mn (0.015) and Co/Mn (0.002) are found in terrigenous and terrigenous-siliceous mixed sediments, respectively. This may indicate the least remobilization of Mn and hence less effect of diagenesis on trace metal enrichment in these sediments.

The overall variability in Ni/Mn (0.015-0.039), Co/Mn (0.002-0.098) and Cu/Mn (0.021-0.11) ratios in CIB sediments, suggests either variations in the local rates of supply of Ni, Cu and Co relative to Mn or heterogeneous distribution of Ni, Cu and Co among more than one sediment fraction. The ratios of Cu and Ni to Mn in the CIB sediments are comparable to those in rough nodules from siliceous sediments (for Cu/Mn) and the smooth nodules from terrigenous and pelagic clay sediments (for Ni/Mn)<sup>37</sup>. This indicates that in these sediments the bulk of Ni resides in the hydrogenous fraction (in case of terrigenous and pelagic clay sediments) and Cu is enriched by the cumulative effect of hydrogenous and diagenetic processes (in case of siliceous sediments).



Figures 2 a-g. Scatter plots of geochemical parameters for surface sediments of the Central Indian basin.

The moderate to poor correlation of Fe and Cu ( $r = 0.56$ , Figure 2 d) may indicate that although major portions of both these trace metals were contributed through different processes, a partial hydrogenous contribution of Cu cannot be ruled out in the CIB sediments.

From the results of the  $Q$ -mode factor analysis (Table 3) of the sediment composition it was observed that the sum of the squares of factors 1-7 are 2.64, 1.45, 1.11, 1.39, 1.25, 0.11 and 0.03 respectively. They account for about 99.79% of the total variance.

Examination of the factor scores shows that the first factor (which accounts for 33.05% of the total variance) has higher loading of Mn, Ni, Cu, Co and Mn/Fe than their average values among all seven factors. The coexistence of the transition metals (Ni, Co and Cu) with Mn in factor 1 possibly indicates the combined effect of hydrogenetic (chiefly for Ni and Co enrichment) and early diagenetic (chiefly for Cu and Mn enrichment) processes in these sediments. The overall trace metal distribution pattern in CIB sediments shows that Mn has a slight decreasing trend towards the southern part of the study area, while Cu shows a nearly constant distribution trend in all sediment facies. Co also shows a near constant distribution trend in all cases except the siliceous sediments, where its concentration is low. Ni enrichment is maximum in mixed terrigenous-siliceous sediments and least in siliceous sediments. Mn/Fe increases sharply towards the southern part of the study area.

As discussed earlier the correlation matrices for specific sediment types show a better correlation between Ni and Co in pelagic clay and terrigenous sediments than in siliceous sediments, possibly because deposition of Ni and Co took place along with ferromanganese oxides through hydrogenetic process on those sediment substrates<sup>25,26</sup>.

The concentration of Ni in the siliceous sediments is less in comparison to pelagic clay and terrigenous sediments. The concentration of Cu in siliceous sediments may have been contributed by the dual process of diagenetic remobilization and hydrogenetic process. The higher concentration of Cu in oceanic water with increase in depth was correlated with the dissolution of certain Cu-enriched species (e.g. Acantharia) below the lysocline by Boyle *et al.*<sup>33</sup>. Observations by Bruland *et al.*<sup>38</sup>, Colley *et al.*<sup>39</sup> and Dymond<sup>40</sup> also supported this type of metal enrichment process. In addition to the early diagenetic process, the enrichment of Cu in the CIB sediments below the lysocline could also have been affected by the process involving the dissolution of biota as discussed above.

Factor 2 (which accounts for 18.18% of the total variance) has the highest loading of Fe. Fe decreases significantly towards the southern part of the study area. The gradual decrease in Fe is probably due to the gradual decrease in the influence of continental influx from the northern to southern part of the CIB, and the mineralogical study of the CIB sediments<sup>8,14</sup> supports this observation.

## RESEARCH ARTICLES

**Table 3.** Varimax-rotated factor matrix for surface sediment samples from the Central Indian basin

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Depth	0.17243	0.10997	-0.13950	0.01991	0.96858	0.00964	0.00040
Mn	-0.93754	-0.17044	0.02548	-0.24455	-0.15342	0.00893	0.08153
Fe	-0.25989	-0.91777	-0.23257	-0.04565	-0.17074	-0.00600	-0.00655
Ni	-0.83150	0.01183	0.16146	-0.45797	-0.21234	-0.06541	-0.14469
Cu	-0.57915	-0.25039	-0.60056	-0.36240	-0.10093	-0.31517	-0.01433
Co	-0.51030	0.08128	-0.03368	-0.85491	0.01922	-0.02058	0.00965
Cu/Ni	0.19769	-0.27109	-0.90843	0.06025	0.24085	0.02245	0.00061
Mn/Fe	-0.58436	0.65402	0.31236	-0.33760	-0.09650	0.01572	-0.03758
Sum of the squares of elements in each factor:							
	2.64	1.45	1.39	1.25	1.11	0.11	0.03
Percentage variance:							
	33.00	18.13	17.38	15.63	13.88	1.38	0.38
Total variance:	99.78%						

Factor 3 (which accounts for 17.31% of the total variance) shows higher loading of Cu/Ni and Cu and a moderate loading of Mn/Fe and Ni. Good correlations exist between Cu and Ni in specific sediment types indicating their enrichment through similar processes. But, the poor correlation of Cu/Ni with Cu in specific sediment types may indicate that the effects of diagenesis on Cu and Ni were not similar in every sediment type. The correlation of Mn/Fe and Ni ( $r = 0.72$ , Figure 2e) in CIB sediments indicates that in addition to the hydrogenetic component, a diagenetic control for Ni enrichment could also be possible.

Although in CIB sediments Co and Ni show good correlation ( $r = 0.64$ , Figure 2f), factor 4 (which accounts for 15.65% of the total variance) shows a high loading of Co, and a moderate enrichment of Ni. This may indicate that the depositional processes of Ni and Co are not always similar, e.g. while deposition of Co is mostly dominated by hydrogenous processes, Ni is contributed by both hydrogenous and diagenetic processes.

Factor 5 (which accounts for 13.92% of the total variance) shows highest loading of water depth and moderate loading of Cu/Ni and Ni, respectively. This indicates that while Ni is possibly contributed in these sediments mostly through the hydrogenetic process, Cu is contributed by a combination of hydrogenetic and diagenetic processes.

Factor 6 (which accounts for 1.38% of the total variance) is dominated moderately by Cu and poorly by Ni. Cu and Ni show good correlation in all sediment types. The present observation possibly indicates that both Cu and Ni were contributed by hydrogenous and diagenetic sources in variable extent, where the major portion of Cu was contributed by the diagenetic process and the major portion of Ni was contributed by the hydrogenetic process.

### Conclusions

(i) Illite and kaolinite + chlorite are predominant in the terrigenous and siliceous sediments, indicating influence

of continental influx. The concentration of these minerals decreases towards the pelagic clay with a corresponding increase in smectite. The presence of smectite points towards a higher input of volcanic materials, the source of which could be the basinal seamounts, mid-Indian ocean ridge or ninety east ridge.

(ii) Ni, Cu and Co are well correlated with Mn in the terrigenous, siliceous and pelagic clay sediments, including their transition zones. The better correlation of Ni, Cu and Co with Mn indicates their incorporation in the Mn phase. The enrichment of Ni, Cu and Co with Mn, may be due to the combined effect of hydrogenetic and early diagenetic processes, which is variable at different geographic locales in the CIB. While early diagenetic process is envisaged to be responsible for the trace metal concentration in siliceous sediments, hydrogenetic contribution is postulated for the pelagic clay and terrigenous sediments. The combined effect of hydrogenetic and early diagenetic processes could be responsible for the trace metal chemistry of terrigenous-siliceous transition zone sediments.

(iii) The average Cu/Mn ratio of CIB sediments is comparable with that in rough nodules from siliceous sediments, and the average Ni/Mn ratio is comparable with that in smooth nodules from terrigenous and pelagic clay sediments. This observation probably indicates that but for copper, bulk of the nickel resides in the hydrogenous fraction, is enriched by the cumulative effect of the hydrogenous and early diagenetic processes. Factor analyses of the sediment chemistry also confirmed these observations.

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