

GEOCHEMISTRY OF SEDIMENT CORES OF THE WESTERN EQUATORIAL INDIAN OCEAN

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ABSTRACT

Geochemical investigations including partition analysis have been carried out on nine sediment cores from the western equatorial Indian Ocean. The results show that a core from the Arabian Sea exhibits a greater terrigenous influence than cores from the Somali Basin, and that among the Somali Basin cores depth appears to influence the variable distributions of metals in them. Iron, aluminium and titanium appear to be mainly supplied from terrigenous sources, manganese from authigenic sources, and the remaining elements from a variety of sources including submarine volcanic activity.

Key-words : Geochemistry, sediments, Indian Ocean.

INTRODUCTION

There have been relatively few investigations on the geochemistry of the deep sea sediments from the western equatorial Indian Ocean and thus little has been published on the nature of the chemical constituents of these sediments, their sources and their conditions of deposition. In order to make a start on solving some of these problems, nine sediment cores were obtained during a cruise of RRS *Shackleton* in the region, in a variety of water depths and tectonic settings (Fig. 1).

In the western equatorial Indian Ocean, the main potential sources of elements to marine sediments will include terrigenous detritus, organic remains, the products of modern submarine volcanic activity from the Carlsberg Ridge, the alteration of ancient volcanic rocks and authigenic minerals. The Indus River is a principal source of terrigenous material to the north-western Indian Ocean, discharging 48×10^{11} gm of sediment into the Arabian Sea (Holeman, 1968), some of which is transported as far as the Carlsberg Ridge (Seibold, 1972). Wind borne transport of terrigenous material to the north western Indian Ocean may also be effective although Kolla, Henderson and Biscay (1976) suggest that it is dominant only in the western part. However, using mineralogical tracers, Goldberg and Griffin (1970) suggested an aeolian contribution to sediments in the north western Indian Ocean from both the Rajasthan desert and the Deccan Traps in India, while Aston, Chester, Johnson and Padgham (1973) favoured the Rajasthan desert as the principal source. As mentioned, a further aeolian input occurs in the western Arabian Sea where sediments are derived from the deserts of Somalia and Arabia (Heezen and Tharp, 1965 ; Goldberg and Griffin, 1970; Kolla, Be and Biscay, 1976).

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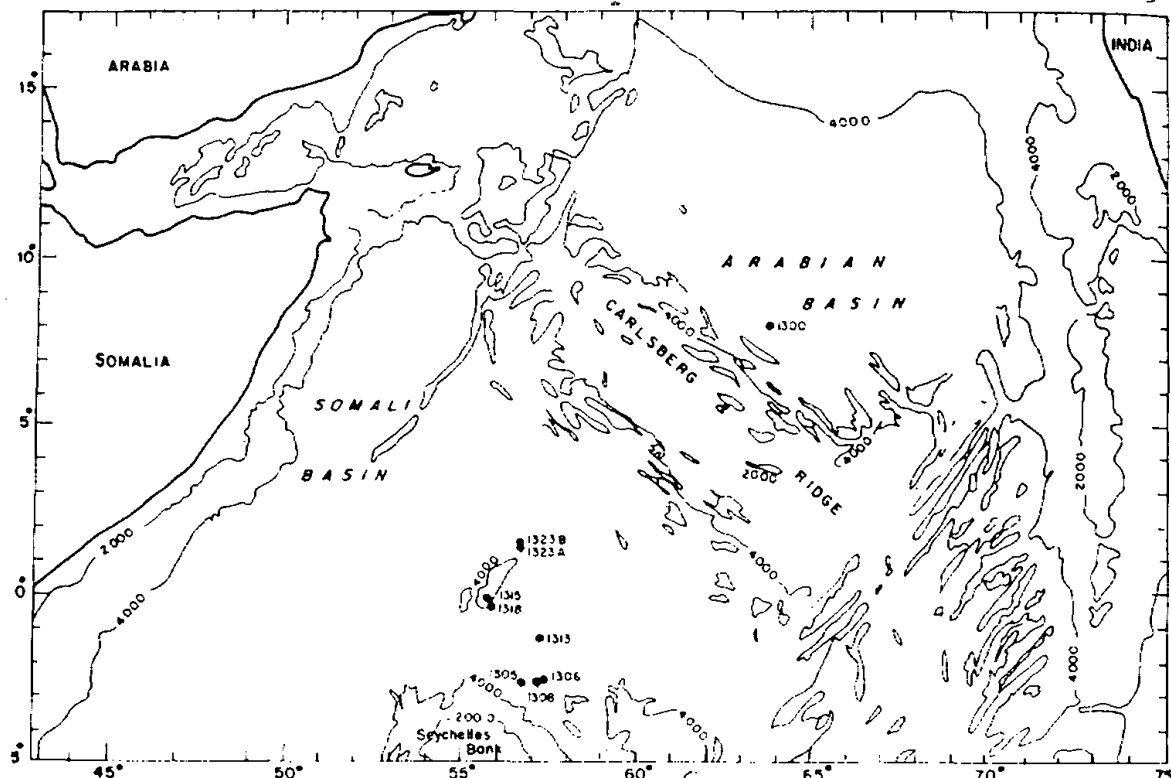


Fig. 1. Map showing the station locations.

Although the present sediments are largely taken from south of the areas considered above, these inputs may supply a variable proportion of elements to them too.

Sinking organic remains will also supply a proportion of the elements to the western equatorial Indian Ocean sediments, but no quantitative estimates have been made. Likewise, volcanic activity might be expected to provide a further proportion of the elements in the sediments (Bostrom, Peterson, Joensuu and Fisher, 1969), most probably through the incorporation of volcanoclastic material and the alteration products of submarine basalt, but again, no quantitative estimates have been made. Finally, the precipitation of minor amounts of authigenic minerals is more or less ubiquitous in deep sea sediments and sometime they comprise a major portion of the sediments (Bonatti, 1963). Once again, their estimates in western equatorial Indian Ocean sediments have not been made.

In the present work, an attempt has been made to obtain estimates of the various proportions of elements that accrue to the sediments from different possible sources.

MATERIAL AND METHODS

The analyses used in this paper were performed using atomic absorption, colorimetric, titrimetric and X-ray Diffraction techniques. Initially, all samples were analysed after total digestion in hydrofluoric and perchloric acids for Fe, Mn, Ni, Co, Cu, Zn and Mg using an Hilger & Watts atomic absorption spectrometer Model H 1550. Al and Ti were determined in all samples

using colorimetric methods following the method of Riley (1958). Calcium carbonate content in the sediments was determined titrimetrically using the method of Muller (1967). The bulk mineralogy of the sediment samples was studied using a Philips X-ray Diffractometer.

Following the bulk analyses for the element concentrations, selective chemical attacks were made on the samples chosen from few levels from each core using an adaption of the leach procedure evolved by Chester and Hughes (1967, 1969). Three accurately weighed representative subsamples, about 1 gm each were obtained from each sample. The first subsample was leached with 10% acetic acid, added slowly until reaction ceased, stirred for 4 hours and then filtered. The second subsample was leached with an excess of mixed acid-reducing reagent consisting of acetic acid and hydroxylamine hydrochloride, stirred for 4 hours and filtered. The third was leached with 50% hot hydrochloric acid and kept hot for 4 hours prior to filtration. The dissolved materials were always filtered through previously weighed filter papers and the residues were weighed. The leach solutions were analysed by atomic absorption spectrometry for Fe, Mn, Ni, Co, Cu and Zn and by colorimetry for Al and Ti, using standards made up in the same solutions as samples. The aim of this procedure was to analyse (i) the carbonate mineral constituents, loosely sorbed ions and interstitial water evaporate soluble in the acetic acid (ii) all these phases together with the ferromanganese oxide phases reducible by hydroxylamine hydrochloride; and (iii) everything including iron oxide minerals, except the most resistant silicates and aluminosilicates insoluble in hydrochloric acid. Because the chemical attacks were made on different subsamples of each sample and not sequentially on individual samples, the portion of each element soluble in HCl but not in acetic acid or hydroxylamine hydrochloride and the portions soluble in hydroxylamine hydrochloride but not in acetic acid were obtained by subtraction.

The precision of the atomic absorption and colorimetric analyses of both bulk samples and leached fractions is better than 10% on the basis of duplicate analyses. The accuracy was checked by analysis of U.S. Geological Survey standard rocks.

RESULTS AND DISCUSSION

Sediment lithology, Stratigraphy and Bulk geochemistry

The vertical distribution of the various elements studied in the different cores are depicted in Figs. 2 to 10 and the range of values as well as the average concentration of each element in the different cores on both bulk sample basis and carbonate free basis are given in Table I. The lithology, stratigraphy and bulk geochemistry of each core is described below.

Core SH. 1300 (Fig. 2): This core was taken from a depth of 4615 m in the Arabian Basin and is mainly terrigenous in character with a detrital content varying from 50 to 64%. It is generally low in biogenic calcium carbonate, decreasing from 30% near the top to 3% at about 30 cm and increasing towards the base. Mineralogically, core SH 1300 is characterised by the presence of orthoclase as a major constituent with muscovite, kaolinite, montmorillonite and aragonite as minor constituents, and illite in trace amounts.

Table 1. Ranges and averages of chemical constituents in the sediments.

Cores	CaCO ₃	Ca%	Mn ppm	Fe%	Al%	Ni ppm	Zn ppm	Cu ppm	Co ppm
SH 1305 A 1	50-88.79	21.14-37.76	158-3000	0.12-2.50	0.16-3.86	7-100	6-80	7-270	1-26
SH 1305 B 1	71.02	29.86	652-11764	0.5-6.36	0.73-9.65	29-445	33-204	62-692	8-116
SH 1306 A 1	68-88.90	31.02-37.6	117-440	0.38-0.54	0.49-0.88	9-44	11-31	19-137	2-40
SH 1306 B 1	81.72	34.50	587-2303	1.22-3.49	1.53-5.11	59-189	63-155	118-457	18-64
SH 1318 A 1	65-96.2	33.6-38.18	23-72	0.073-0.113	0.07-0.23	7-30	5-13	2-139	6-12
SH 1318 B 1	89.15	36.66	410-1883	0.21-2.23	0.66-2.76	86-718	14-334	42-397	23-269
SH 1313 A 1	66.0-82.41	26.31-34	939	1.55	1.84	316	143	126	143
SH 1313 B 1	74.97	30.50	255-1103	0.863-1.79	1.26-2.70	25-64	26-51	36-99	9-19
SH 1300 A 1	3.15-32.81	1.77-14.0	1321-3534	3.86-5.80	4.96-8.71	132-275	124-185	185-395	37-70
SH 1300 B 1	19.97	9.06	633	1.175	1.78	44	36	65	13
SH 1323 A 1	77-88.59	33.6-35.18	2598	4.58	7.41	183	152	263	52
SH 1323 B 1	84.84	34.65	896-3260	3.68-5.4	5.14-7.46	101-190	96-163	76-153	10-49
SH 1308 A 1	81-87.12	32-38.4	1012-3628	5.22-6.71	6.34-8.30	114-244	123-223	86-259	14-51
SH 1308 B 1	84.38	35.09	2033	4.54	6.14	145	121	141	27
SH 1323 A 2	78-87.17	32-38.4	2579	5.69	7.70	182	152	144	34
SH 1323 B 2	81-87.12	32-38.4	40-344	0.337-0.965	0.54-0.79	10-38	15-29	15-31	3-18
SH 1308 A 2	82-89.95	34.82-36.0	200-273	1.934-3.780	2.52-5.76	70-246	85-156	105-181	25-92
SH 1308 B 2	86.51	35.20	108	0.47	0.64	21	19	21	9
SH 1323 A 2	82-89.95	34.82-36.0	804	2.95	4.44	139	125	144	59
SH 1323 B 2	86.51	35.20	118-360	0.368-0.567	0.57-1.39	15-36	14-24	27-87	5-12
SH 1315 A 1	80-96.97	36.8-39.2	912-2722	1.04-4.15	3.0-6.53	117-174	110-138	205-458	23-62
SH 1315 B 1	90.55	37.92	265	0.46	0.81	24	18	50	7
SH 1315 A 2	80-96.97	36.8-39.2	1781	3.09	5.26	151	120	299	45
SH 1315 B 2	90.55	37.92	561-1420	0.41-0.62	0.47-1.34	30-48	15-35	18-166	11-20
SH 1315 A 1	80-96.97	36.8-39.2	3446-9466	3.03-4.57	4.68-8.37	212-455	112-233	142-196	84-165
SH 1315 B 1	90.55	37.92	819	0.53	0.78	41	20	20	15
SH 1315 A 2	80-96.97	36.8-39.2	6191	4.01	5.64	313	148	167	116
SH 1315 B 2	90.55	37.92	200-380	0.092-0.213	0.07-0.26	8-34	4-8	3-148	8-20
SH 1315 A 1	80-96.97	36.8-39.2	1052-10500	0.75-5.87	0.79-2.48	84-440	20-182	83-141	42-509
SH 1315 B 1	90.55	37.92	266	0.16	0.12	18	6	44	14
SH 1315 A 2	80-96.97	36.8-39.2	5517	3.16	1.68	274	102	98	275

Column A (1) Range of values on bulk sample basis. (2) Range of values on CaCO₃ free basis.Column B (1) Average values in the core on the bulk sample basis. (2) Average values in the core on the CaCO₃ free basis.

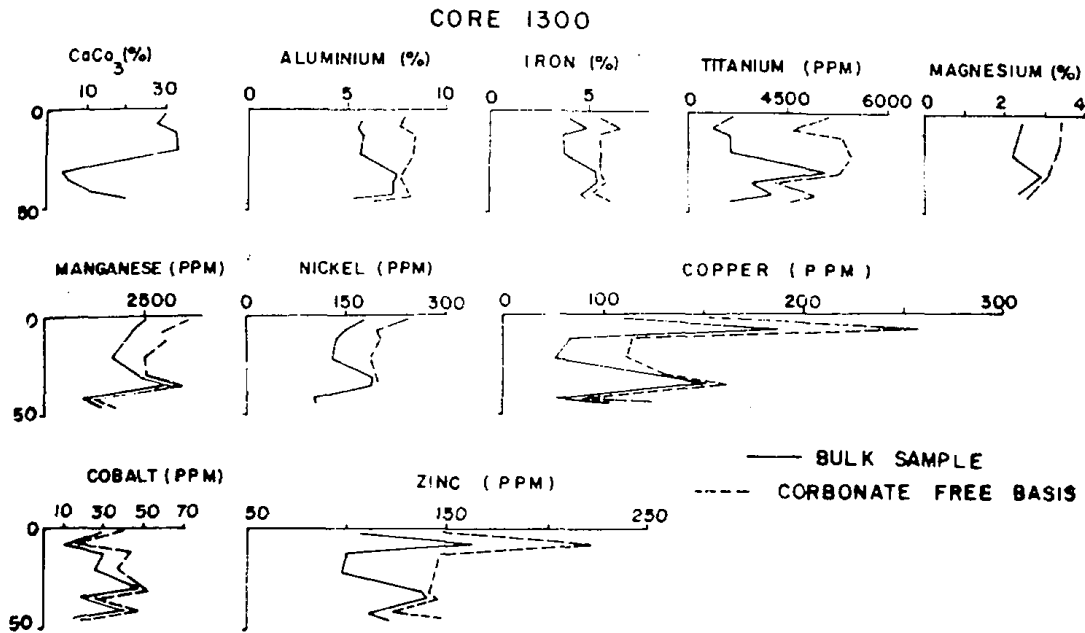


Fig. 2. Vertical distribution of various elements in the core number 1300.

The nanoplankton assemblage in this core places it entirely in the *Gephyrocapsa oceanica* zone of Late Quaternary age.

Iron, titanium and aluminium do not vary significantly down the core ranging between 3.5–5%, 0.4–0.5% and 5–7.5% respectively. Magnesium also varies little being between 2 and 3%. Manganese and nickel show similar trends, the former decreasing from about 2500 ppm to 1000 ppm from the top to the bottom of the core and nickel from about 170 to 100 ppm. Copper and zinc show some similarities in their distribution in that each one increases from about 100 ppm at the surface to 160–190 ppm at 10 cm and then decreases to 70–90 ppm at about 20 cm and then increases again at around 30 cm depth. Cobalt varies somewhat irregularly between 10 and 50 ppm. Titanium varies from about 3500–5000 ppm but shows no particular covariance with the other elements determined.

Core SH. 1305 (Fig. 3): This core was taken in the Somali Basin at a depth of 4369 m, close to the foot of the Seychelles Bank. The lithology is quite variable with frequent minor colour changes and variations in texture. Overall it is calcareous in nature, with CaCO_3 varying from about 50% to 85% averaging about 70% and a detrital content varying from just a few percent to 25%. At 85–89 cm depth, there is a layer rich in terrigenous material while at 175–200 cm occurs a richly calcareous layer of turbiditic appearance. It may have resulted from slumping of coarse calcareous detritus down the Seychelles Bank. Mineralogically, calcite is the main constituent with minor amounts of aragonite, kaolinite, muscovite and orthoclase and biotite, hematite and goethite in traces. Like core SH 1300 the nanoplankton assemblage places the sediments in the *Gephyrocapsa oceanica* zone of Late Quaternary age.

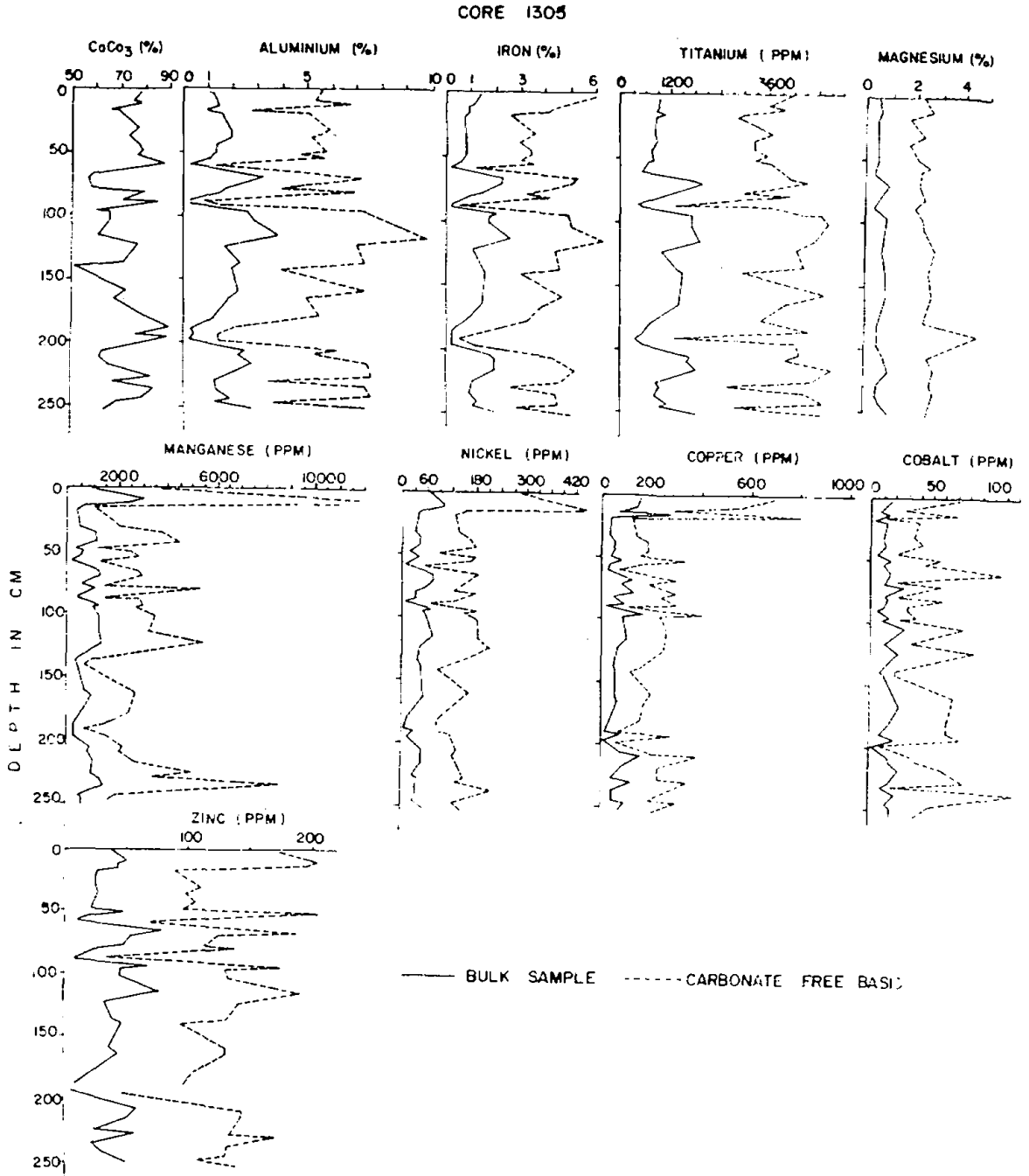


Fig. 3. Vertical distribution of various elements in the core number 1305.

This core exhibits significant geochemical variations. Aluminium and iron show similar trends throughout the core, except the surface layer which is enriched in iron more than immediately below, but not in aluminium. Titanium varies somewhat irregularly down the core ranging from 300 ppm upto about 2000 ppm but shows some similarity with the distribution of iron. Manganese and nickel show similarities in their distribution down the core, particularly in that each is enriched in the sediment just below the surface and

then vary rather irregularly near the base. Zinc also shows an enrichment in the sediments just below the surface of the core, but thereafter varies more widely than manganese and nickel. Copper shows an extreme enrichment to 270 ppm at about 17 cm, just below the level at which manganese and nickel are enriched, and thereafter varies between about 30 and 150 ppm down the remainder of the core. Magnesium averages about 0.6% down the core but increases to about 1.0% at 200 cm.

The effect of the calcareous turbidite layer on the composition of the core is quite clear. Magnesium almost doubles in the middle of this layer, probably due to the presence of high magnesium calcite. The contents of Fe, Al, Ti, Cu and Zn decrease within the turbidite.

Core SH. 1306 (Fig. 4): This core was taken in 3983 m water depth at the foot of a seamount to the N.E. of the Seychelles. It is relatively uniform in appearance with calcium carbonate content varying between about 68 and 88% and detrital content of 4-6%. Apart from calcite, it contains orthoclase, muscovite and kaolinite in small amounts and biotite, hematite and goethite in trace amounts. It is Late Quaternary in age.

Because of the lithological uniformity, most of the elements in the core exhibit little geochemical variability (Fig. 4). Aluminium averages about 0.6%, Fe 0.4%, Ti 0.06%, Mn 247 ppm, Ni 21 ppm, Zn 15 ppm Mg 0.29%. Copper varies more widely but the range is not extreme.

Core SH. 1308 (Fig. 5): This core was taken from the same seamount as

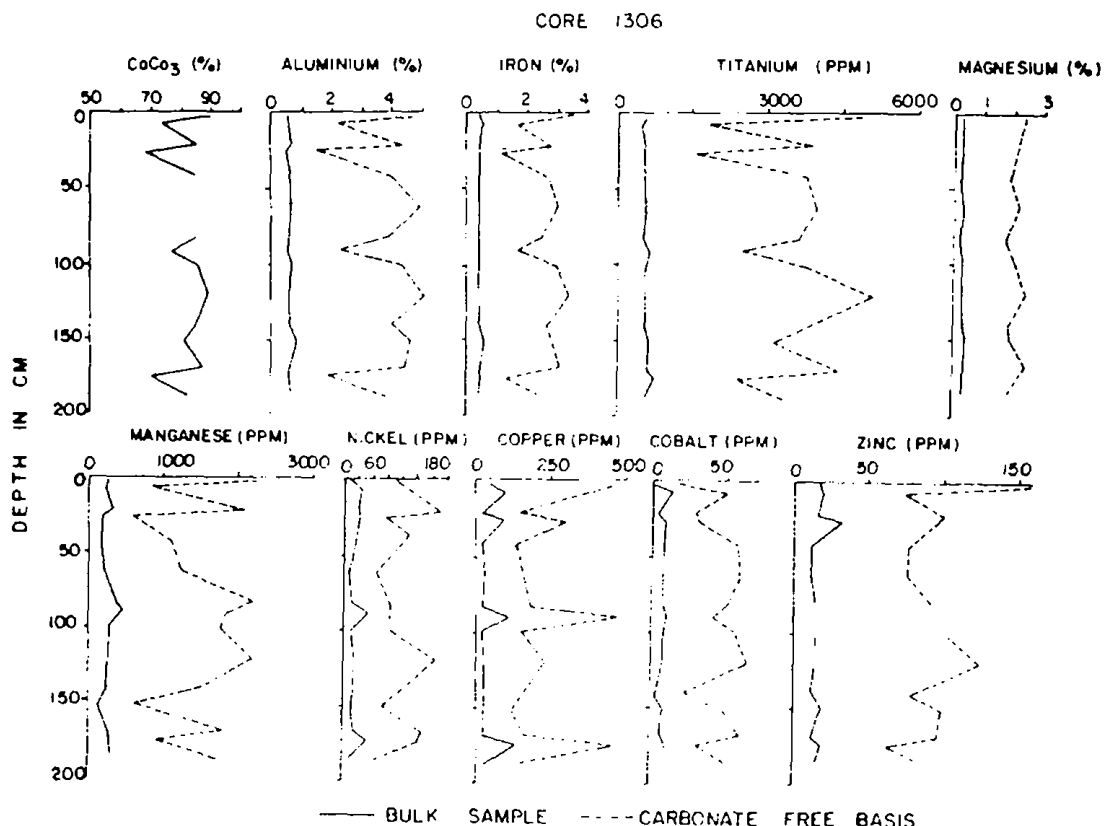


Fig. 4. Vertical distribution of various elements in the core number 1306.

SH 1306 but at a depth of 3231 m. It is a lithologically uniform calcareous sand with calcium carbonate content of about 78–87% and a detrital content of around 4% consisting minor amounts of orthoclase, kaolinite and muscovite, Like the other cores so far described, it is Late Quaternary in age.

This core shows only minor chemical variations down its length (Fig. 5). However, Mn, Ni, Cu and Zn exhibit a minimum at about 11 cm depth. By contrast Fe, Co and Mg vary hardly at all.

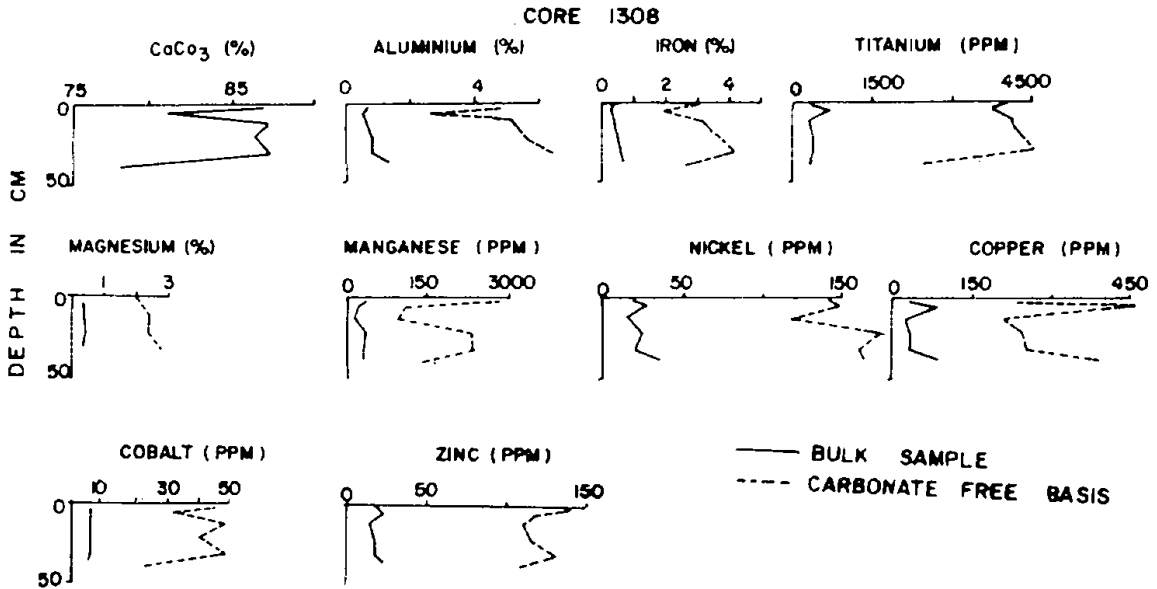


Fig. 5. Vertical distribution of various elements in the core number 1308.

Core SH. 1313 (Fig. 6): This core was taken from a depth of 4404 m in the Somali Basin north of the seamount where SH 1306 and 1308 were taken, and consists of a uniform calcareous ooze throughout. Calcium carbonate content varies from 66 to 82% and it also contains the detrital minerals as found in other cores other than SH 1300 with concentrations between 11 and 20%. It is Late Quaternary in age.

Al and Fe covary quite closely, with Ti showing a similar distribution (Fig. 6). Mn, Ni, Co and Cu show certain features in common. They all increase towards the base of the core, as does Zn too. Mg exhibits little over all variation.

Core SH. 1315 (Fig. 7): This core was obtained from a depth of 1200 m on the top of a seamount north of the Seychelles and consists of a foram sand of relatively uniform lithology. It varies in calcium carbonate content between about 80 and 97%. Ferromanganese oxide coating of the foram tests occurs commonly throughout the core. Its detrital mineral content is less than 5% and its age has been determined as Late Quaternary on the basis of *Gioborotalia truncatulinoides*. Being very high in calcium carbonate content, this core exhibits low concentrations of most other constituents (Fig. 7). Al increases in an irregular manner towards the base of the core, Fe and Ti vary hardly at all, nor do Mn and Cu although they do show a slight increase towards the base of the core. Mg and Zn exhibit no clear trends whereas Ni peaks about halfway down the core.

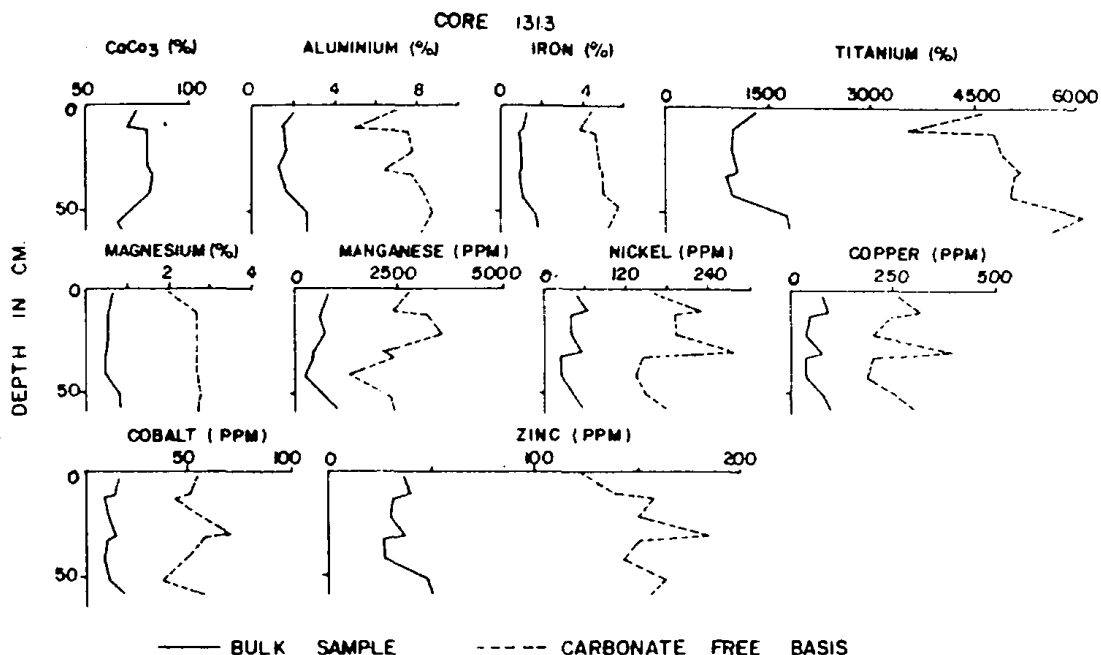


Fig. 6. Vertical distribution of various elements in the core number 1313.

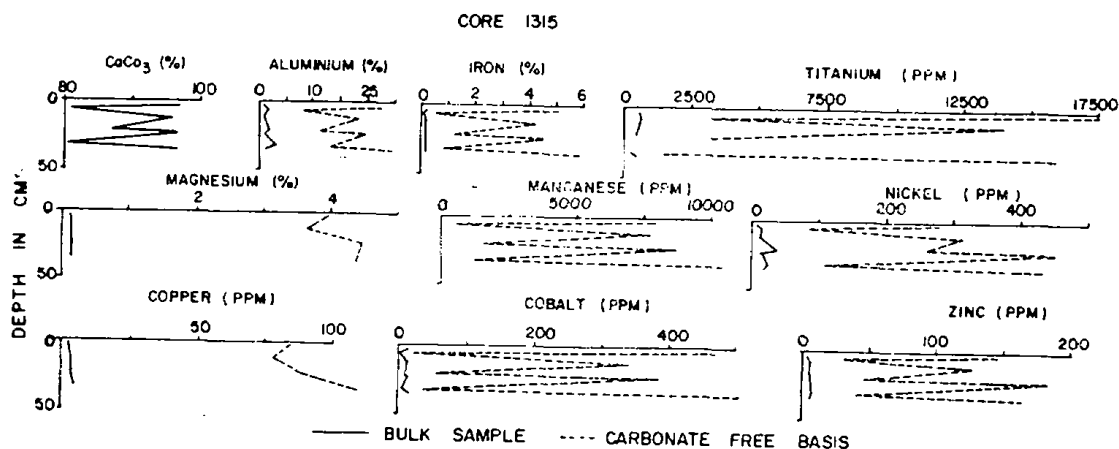


Fig. 7. Vertical distribution of various elements in the core number 1315.

Core SH 1318 (Fig. 8): This core was taken close to SH 1315 at a depth of 1358 m and also consists of foram sand. It contains about 95% CaCO_3 throughout, except for a layer in which it drops to about 65%. Its detrital content is minimal. Al, Fe and Ti all appear to covary, increasing towards the base, although Al exhibits its highest value near the middle of the core. By contrast Mn, Ni and Zn decrease towards the base of the core, Co shows no clear trend and Al and Cu peaks near the centre of the core where CaCO_3 is lowest.

Core SH 1323 A (Fig. 9): This core was taken at a depth of 2800 m from another seamount to the north of the Seychelles. Throughout, it is a calcareous ooze with CaCO_3 varying from about 77–89%. Its detrital content is

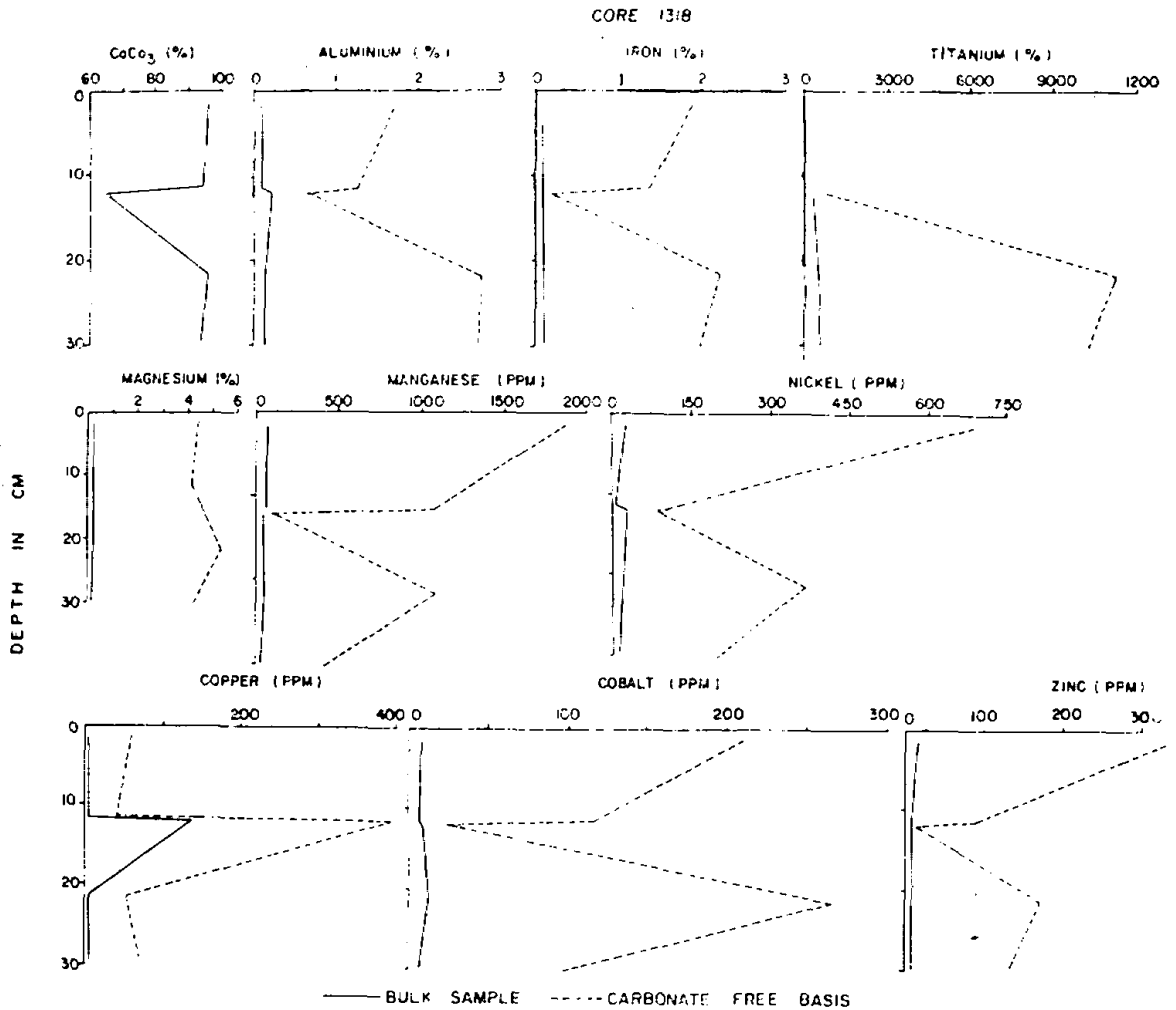


Fig. 8. Vertical distribution of various elements in the core number 1318.

low (5–7%) consisting of a similar mineral assemblage to those cores already described other than SH 1300. It is Late Quaternary in age. Al and Fe covary in this core as they do in SH 1318 and show a clear minimum between about 20–40 cm. Mg also shows a similar trend. By contrast, Mn is the highest in this interval. The minor elements Ni, Co and Cu vary rather irregularly down the core but show a small peak at about 50 cm, as also does Zn.

Core SH 1323 B (Fig. 10): This core was taken very close to SH 1323 A on the same seamount but from a slightly greater depth (2940 m). It also consists of a calcareous ooze throughout with CaCO₃ varying from 80–90% and contains an even smaller detrital fraction (2.4–4%) than SH 1323 A.

It is of particular interest to note that although cores SH 1323 A and B were taken from very close locations with a difference of 140 m water depth, they are widely different in age. Core SH 1323 B has been assigned a Lower Pliocene age on the basis of the presence of *Reticulofenestra pseudumbilica*.

Mn is higher in SH 1323 B than in SH 1323 A. Mg and minor elements appear to exhibit little consistent variation, although Zn peaks with Mn at

about 21 cm depth. The distribution of Fe, Al and Ti show some features in common but the covariance between them does not appear to be as close as in some of the other cores studied.

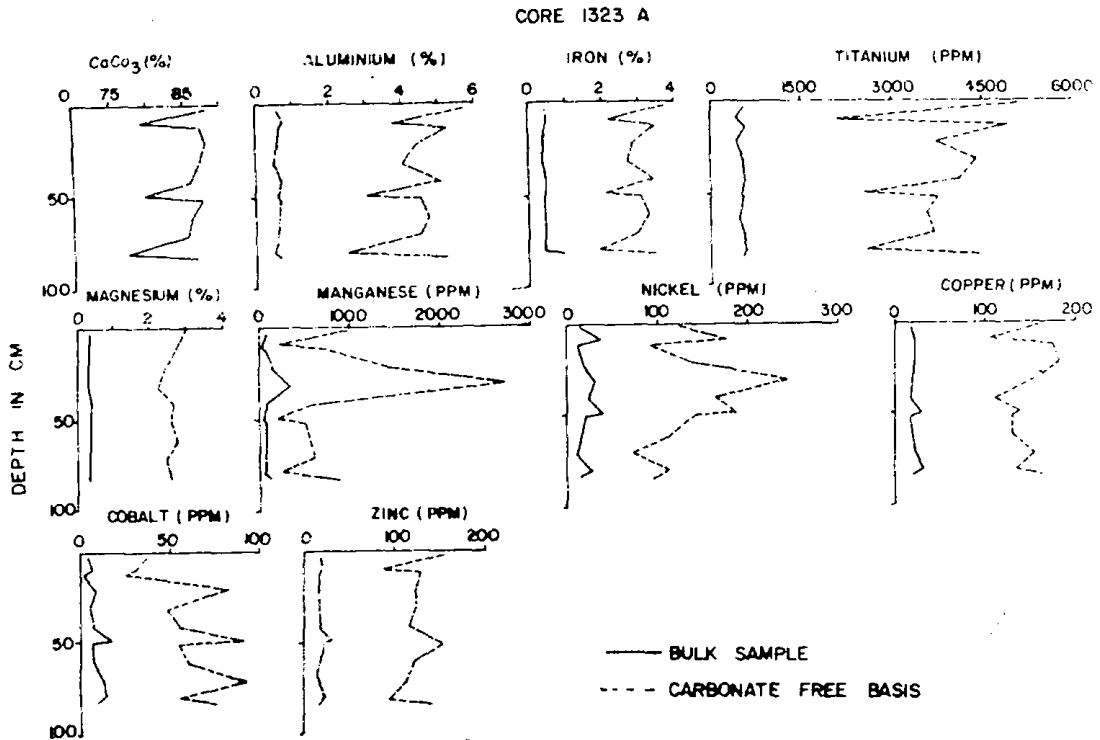


Fig. 9. Vertical distribution of various elements in the core number 1323A.

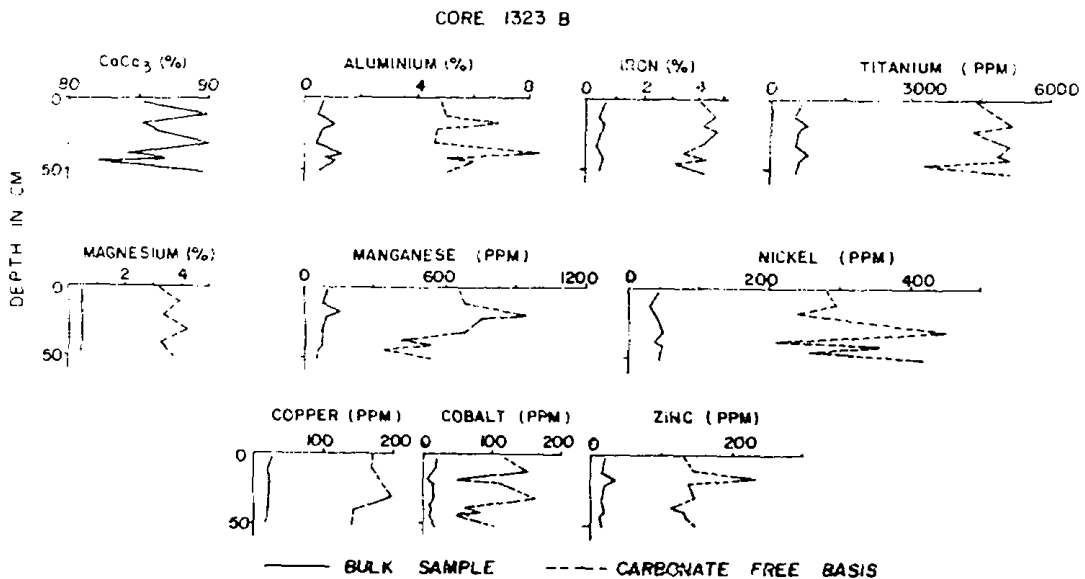


Fig. 10. Vertical distribution of various elements in the core number 1323B.

Interrelationships among the elements

In order to understand the overall relationships among the various elements in the cores studied, correlation coefficients have been calculated and the data is presented in Table II in the form of a matrix. An analysis of the data reveals the following trends: (i) Fe, Co and Zn exhibit a significant relationship with Al while Mn, Ni and Cu do not; (ii) The covariance between Mn and Fe is highly significant; (iii) Nickel and Zinc show a significant correlation only with both Fe and Mn; (iv) Cobalt shows a significant correlation only with Mn, and not with Fe; (v) Copper does not exhibit any correlation with Fe and Mn and (vi) among Ni, Co, Cu and Zn, there is a significant correlation between Ni and Co, Ni and Zn, Co and Cu and Co and Zn, but there is no correlation at all between Ni and Cu and Cu and Zn.

Table II. Correlation co-efficients between elements in the samples.

	Al	Fe	Mn	Ni	Co	Cu	Zn
Al	1.00						
Fe	0.8436**	1.00					
Mn	0.1814	0.3455**	1.00				
Ni	0.0169	0.2566**	0.3947**	1.00			
CO	0.2550	0.1063	0.2795**	0.5353**	1.00		
Cu	0.0610	0.1179	0.0104	0.0042	0.31	1.00	
Zn	0.4129**	0.5832**	0.2496*	0.6539**	0.2549*	0.1527	1.00

Degrees of freedom : 104. ** Highly significant 95%. * Significant 95%.

PARTITION ANALYSIS

Using the methods described earlier in this work, all the cores have been subjected to geochemical partition analysis. Partition values for each of the elements in each core are given in Table III.

Iron: Iron is mainly present in the HCl soluble and insoluble fractions of the sediments where it is likely to be present in iron oxides, clays and resistant detrital minerals. It is more concentrated in the HCl soluble fraction of cores 1300, 1305 and 1313 than in the HCl insoluble residues whereas the reverse is the case in the remaining cores. It does not occur to any significant extent in the acetic acid soluble carbonate fraction of the sediments, and is present in only minor proportions in the acid reducible ferromanganese oxide fraction.

Manganese: With the exception of cores 1323 A and 1318, the bulk of the manganese in all the sediments is housed in their acid reducible ferromanganese oxide fraction. In core 1323 A, a greater portion of the very low

manganese content is present in the acetic acid soluble fraction, where it may occur partly as coatings on the carbonate tests which have been dissolved by the action of the acetic acid. In core 1318, it is more evenly partitioned between the different phases of the sediments. Manganese is present in variable but minor concentrations in the HCl soluble and insoluble fractions of most of the sediments, where it probably occurs in lithogenous phases.

Nickel : The partition of nickel is variable between the different cores studied. In core 1300, the bulk of the relatively abundant Ni present is mainly held in the HCl soluble fraction where it is probably associated with oxide and clay minerals, with subordinate amounts associated with the acetic acid soluble and HCl insoluble fractions. By contrast, in core 1305, it exhibits a more even partition between these three fractions. In cores 1313 and 1318, most of the nickel is present in the HCl insoluble residue where it is probably present in the resistant detrital phases, while in other cores, significant amounts are held in the acetic acid soluble fraction, with minor amounts in the HCl soluble and insoluble fractions. Surprisingly, apart from a few discrete intervals in some cores, Ni is not present to any significant extent in the acid reducible ferromanganese oxide fraction of the sediments indicating that its frequent association with ferromanganese oxide minerals (Chester and Hughes, 1969 ; Cronan, 1976 and others) is not seen in the present cores.

Zinc : In contrast to Ni, Zn is concentrated to a large extent in the acid reducible phases of the sediments, with subordinate amounts associated with the HCl soluble fractions and HCl insoluble residue. It is not associated with the acetic acid soluble carbonate fraction to any significant extent.

Copper : A major portion of the Cu is contained in the HCl insoluble residue of the sediments where it is probably present in detrital minerals. This is particularly so in cores 1305, 1306, 1308, 1313 and 1323. Greater amounts of the remainder of the Cu are associated with the acetic acid soluble carbonate fraction.

Aluminium : Most of the Al in all the cores is concentrated in the HCl soluble fraction where it is likely to be present in the clay minerals. The second largest proportion of Al in the cores is in the HCl insoluble residue where it probably occurs in the more acid resistant fraction of clay minerals and aluminosilicate minerals. Insignificant amounts of Al are associated with the acetic acid soluble and acid reducible phases.

Titanium : Like Ni, Ti shows no consistent partition pattern between the different cores. In cores 1300, 1305 and 1313, the highest proportion of Ti is present in the HCl insoluble residues, with lesser amounts in their HCl soluble fraction. Whereas there is an appreciable amount of Ti in the acetic acid soluble fraction of core, 1305, the same is not found in cores 1300 and 1313. Only minor amounts of Ti are generally present in the acid reducible fraction of these three cores. In core 1306, Ti is present largely in the acetic acid soluble and HCl insoluble fraction. In cores 1318, Ti is present in the acid reducible fraction and the HCl insoluble residue, with undetectable amounts in the other two fractions.

Table III. Partition analyses.

	Aluminium %					Iron %					Manganese ppm				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
SH-1305															
0-5	1.23	7.2	0.08	91.9	0.8	1.365	0.3	3.5	60.6	35.5	830	20.5	65.0	3.6	10.8
8-12.5	1.35	6.8	0.5	68.1	24.4	1.116	0.1	2.7	69.4	27.9	3000	9.5	26.8	40.3	23.3
15-17	0.9	7.7	—	—	—	0.934	0.6	4.9	79.6	14.8	524	23.3	37.8	1.9	2.7
50-53	1.13	2.5	1.4	78.8	17.7	0.696	0.3	5.0	74.2	20.5	590	37.3	40.6	12.2	9.8
65.5-70	2.57	2.3	2.3	81.3	14	2.25	0.1	3.9	73.8	22.2	1200	21.0	55.5	21.6	1.7
76-80	1.67	2.9	7.7	70	25	1.375	0.1	2.3	79.8	17.8	616	42.5	28.6	28.6	0.3
85-90	0.22	5.9	8.6	—	—	0.152	0.9	9.7	35.4	53.9	428	52.3	32.2	15.9	0.5
93-97	2.31	1.9	1.3	78.8	18.2	1.955	0.1	1.4	75.2	23.27	1175	30.9	11.6	7.2	7.6
114-116	3.86	1.2	2.3	83.9	12.7	2.5	0.44	2.44	77.5	20.0	1205	21.6	55.0	18.7	4.6
139.5-143.5	1.93	2.5	1.3	77.7	18.6	1.46	0.07	2.1	82.4	14.9	326	38.0	3.1	35.6	24.5
162-167	1.71	1.5	1.9	78.9	17.5	1.32	0.12	2.9	79.2	17.7	920	46.7	1.1	45.6	6.5
190-195	0.32	ND	15.9	—	—	0.126	1.4	8.0	4.8	83.3	166	77.0	—	12.0	10.8
206-211	2.11	7.4	—	—	—	1.8	0.1	2.6	85.0	12.2	820	6.9	48.5	33.8	11.6
22-232	1.16	3.0	1.7	94.4	0.8	0.872	0.2	2.4	53.0	44.3	1210	42.6	0.3	56.2	0.8
244-248	1.17	3.0	2.4	46.0	47.8	0.894	0.2	7.1	75.1	17.7	566	52.6	18.0	28.2	1.1
SH-1306															
4.5-9.5	0.56	11.4	2.3	—	—	0.4420	0.84	9.75	0.27	89.14	218	23.4	54.6	0.9	21.1
23.5-28	0.49	2.4	2.8	59.0	34.6	0.3880	0.2	4.7	33.5	66.6	188	22.3	37.2	14.9	25.5
87-92	0.54	4.1	2.2	77.0	16.6	0.3980	0.3	8.2	1.3	90.3	440	15.9	59.5	13.9	10.9
172.5-177	0.58	3.3	5.0	81.0	10.0	0.4620	0.3	19.4	0.8	79.4	276	19.2	58.3	18.3	14.1
SH-1318															
9-14	0.23	2.2	3.5	—	—	0.0750	1.3	5.9	4.8	88.0	38	34.2	18.4	36.8	10.5
SH-1313															
9-11	1.39	3.6	0.4	78.4	17.3	1.0800	1.4	2.3	82.6	13.7	666	30.3	3.6	50.1	0.9
29-31	1.26	7.1	—	48.0	44.0	0.9650	0.3	4.5	10.9	84.3	422	17.8	53.8	7.8	20.6
55.5-57.5	—	0.046	0.032	1.82	—	—	—	—	—	—	—	—	—	—	—
SH-1300															
6-10	5.4	0.9	0.8	67.0	31.3	4.9	0.2	3.1	84.5	12.2	2135	24.5	66.8	17.8	0.2
33-36	7.2	0.8	1.4	55.1	42.6	5.4	0.2	4.8	93.2	1.9	3260	14.0	86.0	—	—
40-44	5.14	0.7	1.2	69.2	28.9	5.025	0.3	3.7	93.5	2.5	1380	23.9	36.6	39.5	—
SH-1323A															
8-10	0.79	4.2	6.3	87.3	2.5	0.45	0.5	16.4	1.6	82.9	48	47.9	27.1	25	—
48-50	0.61	2.1	2.7	68.8	26.2	0.408	0.2	4.2	16.0	79.6	40	65	15	20	—
79-81.5	0.58	2.1	4.1	58.6	34.4	0.445	0.6	7.0	7.2	85.2	56	62.5	8.9	25	3.6
SH-1308															
2.5-7.5	0.57	6.5	1.9	47.4	43.8	0.368	1.4	15.9	5.3	77.4	200	17.5	76.5	5.0	1
36-40	1.39	2.0	1.1	35.2	61.8	0.567	0.5	7.1	8.5	84.0	298	16.1	57.7	13.4	12.8
SH-1323B															
16.5-18.5	1.05	1.2	3.4	—	—	0.622	0.3	—	—	50.1	1420	3.9	94.7	1.4	—
37-39	1.34	0.9	2.4	33.6	63.4	0.546	0.6	—	—	16.3	654	10.4	48.6	41.0	—
43-44	1.08	—	—	—	—	0.546	0.1	3.1	75.2	2.7	620	13.4	19.5	62.1	4.8
SH-1315															
3-7	0.15	18.7	18.0	NIL	66.7	0.092	9.6	—	—	78.3	200	27	50	2.0	3
19-21	0.15	5.3	21.3	NIL	73.3	0.156	4.9	—	—	80.1	200	36	59	2.5	2.5
30-32	0.26	3.1	17.3	NIL	80.7	0.15	7.7	—	—	77.3	234	32.5	61.1	0.4	6.0

A = Bulk Sample, B = Acetic Acid Leach, C = Acid Reducing Mixture,
D = Hot 50% HCl, E = Acid Insolubles.

Titanium ppm					Nickel ppm					Copper ppm				
A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
924	16.2	3.4	12.7	57.7	65	36.9	—	21.5	41.5	155	16.8	11.0	—	72.3
924	20.0	—	12.2	67.7	100	20	8	48	24	139	22.3	3.6	18.7	55.4
1073	8.8	2.1	10.3	78.7	32	26.9	42.8	7.7	23.1	270	7.0	1.1	1.5	90.4
775	24.6	8.0	5.8	61.5	44	36.4	6.8	15.9	40.9	80	16.3	18.8	—	65.0
1759	3.9	8.3	18.3	69.5	79	22.8	16.4	43.0	17.7	125	13.6	24.8	27.2	34.4
1282	3.8	8.9	19.9	67.5	56	21.4	1.8	73.2	3.6	130	11.5	11.5	13.8	63.1
387	—	—	—	—	36	44.4	5.5	3.1	38.8	89	14.6	3.4	4.5	77.5
1759	10.1	0.1	27.1	62.8	74	22.9	—	44.6	32.4	158	17.1	1.9	31.6	49.4
1908	7.1	1.8	31.7	58.8	76	17.1	14.5	30.3	31.6	101	20.8	33.7	38.6	6.9
1490	5.5	6.5	7.9	80.0	44	20.5	9.0	61.4	31.8	60	16.7	21.7	45.0	16.7
1371	4.9	6.1	28.0	60.9	50	28.0	8.0	34.0	30.0	59	28.8	1.7	54.2	15.3
828	32.9	10.6	10.9	45.4	29	55.2	6.9	6.9	31.0	74	13.5	—	46.0	40.5
1580	—	13.2	5.7	79.2	50	28.0	16.0	40.0	16	157	11.5	20.4	19.1	49.0
894	12.1	1.1	—	86.7	46	43.5	45.6	2.2	8.7	123	20.3	2.4	3.3	74.0
894	—	49.8	3.5	46.6	32	31.3	15.6	43.8	9.4	97	16.5	6.2	14.4	62.9
477	51.4	—	—	—	34	70.6	8.8	5.9	14.7	100	17	7	2	74.0
507	53.6	—	—	—	26	53.8	19.2	7.7	19.2	98	13.3	7.1	4.1	75.5
596	41.4	—	58.6	—	44	40.9	9.1	22.7	27.3	116	17.2	4.3	0.9	77.6
715	30.5	—	1.5	68.0	44	40.9	13.6	9.1	36.4	137	13.3	21.9	2.9	62.0
268	—	59.7	—	40.3	30	20	16.7	6.7	56.7	139	2.9	0.7	0.7	95.7
984	5.5	12.9	24.0	57.6	64	18.8	6.3	28.1	46.8	89	66.3	1.1	15.7	16.9
1043	13.0	2.2	19.0	65.8	55	25.5	9.1	5.5	6.0	79	19.0	11.4	21.5	48.1
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
3339	2.8	1.6	43.7	51.8	143	18.9	0.7	65.7	14.7	189	7.4	21.6	33.8	37.0
3994	—	3.1	42.2	51.7	185	16.2	23.8	55.1	4.9	153	14.4	45.8	34.6	5.2
3137	—	4.9	27.9	67.0	104	7.7	10.6	62.5	19.2	102	11.8	36.3	21.6	30.4
447	18.3	48.3	7.6	25.7	18	18.4	28.9	7.9	44.7	22	22.7	50.0	—	—
507	21.5	—	—	27.2	37	32.4	18.9	18.9	29.7	28	25.0	7.1	14.3	53.6
596	22.8	16.1	61.0	—	26	50.0	16.2	3.8	16.2	31	41.1	3.2	25.8	29.0
715	17.2	35.4	39.0	8.4	28	60.7	17.8	3.6	17.9	87	20.7	20.4	2.3	66.7
536	33.0	2.4	53.5	11.0	36	44.4	27.7	13.8	13.8	86	17.4	10.5	9.3	62.8
775	10.6	43.1	69.5	—	36	41.6	8.3	44.4	5.5	166	6	3	4.2	86.7
775	—	76.9	7.7	15.4	34	44.1	26.4	29.4	—	170	8.2	2.4	2.4	87.1
596	9.1	60.7	30.2	—	46	65.2	—	17.4	17.4	160	11.3	1.3	3.1	84.4
596	—	41.6	41.6	—	16	50.0	—	—	—	18	27.7	—	—	—
117	25.9	33.6	37.6	2.9	34	41.2	26.5	—	32.4	130	7.7	—	—	—
298	—	60.1	13.8	26.2	22	63.6	36.4	—	—	148	9.5	—	—	—

Values in Columns B,C,D,E are in % of the total samples, i.e. A.

Table III — Continued

	Zinc ppm					Cobalt ppm					Calcium %		
	A	B	C	D	E	A	B	C	D	E	A	B	E
SH-1305													
0-5	39	25.6	12.8	43.6	17.9	16	43.8	56.2			1.2	—	—
8-12.5	52	38.5	5.8	25.0	30.8	7	57.1	42.9			31.2	95.5	4.5
15-17	45	13.3	64.4	15.6	6.7	4	100.0	—			31.2	84.6	15.4
50-53	49	12.2	59.1	—	—	10	70.0	30.0			34.4	88.4	11.6
65.5-70	80	2.5	42.5	20	35	10	50.0	50.0			24.0	95.8	4.2
76-80	49	4.1	69.4	16.3	10.2	10	40.0	60.0			28.0	81.4	18.6
85-90	10	—	—	—	—	10	100.0	—			36.8	76.1	23.9
93-97	69	2.9	1.4	55.0	27.5	14	42.9	57.1			26.0	92.3	7.7
114-116	—	—	—	—	—	13	30.8	53.8			28.0	85.7	14.3
139.5-143.5	48	2.1	29.2	45.8	22.9	10	70.0	30.0			26.8	74.6	25.4
162-167	45	2.2	51.1	22.2	24.4	22	45.4	44.6			30.4	86.8	13.2
190-195	—	—	—	—	—	18	22.2	77.8			37.6	84.0	16.0
206-211	59	1.7	49.2	20.3	28.8	14	28.6	71.4			24.0	100	—
22-232	60	3.3	41.7	35.0	20.0	—	—	—			31.2	83.3	16.7
244-248	36	2.8	50.0	47.2	—	16	18.75	81.25			32.8	81.7	18.3
SH 1306													
4.5-9.5	19	10.5	—	89.5	—	13	61.5	38.5			35.2	82.95	17.05
23.5-28	31	6.5	87.1	6.5	—	10	90	10			37.6	72.3	27.7
87-92	—	—	—	—	—	10	100	—			36.0	84.4	15.6
172.5-177	19	15.8	52.6	15.8	15.8	9	100	—			31.2	89.7	10.3
SH-1318													
9-14	5	20	80	20	—	8	100	—			33.6	77.4	22.6
SH-1313													
9-11	39	15.4	84.6	—	—	14	50	50			30.4	94.7	5.3
29-31	37	5.4	35.1	21.6	37.8	14	42.8	57.2			34.0	94.1	5.9
55.5-57.5	—	—	—	—	—	—	—	—			—	—	—
SH-1300													
6-10	163	1.2	92.6	4.3	1.8	10	30	70			14	77.1	22.9
33-36	140	1.4	37.1	44.3	17.1	18	—	—			2.4	83.3	16.7
40-44	120	0.8	79.2	5.0	15.0	14	35.7	64.3			—	—	—
SH 1323A													
8-10	18	5.5	88.1	5.5	—	7	71.4	28.6			34.4	91.8	8.2
48-50	29	6.9	45.8	34.5	13.8	18	55.5	44.4			33.6	95.2	4.8
79-81.5	88	13.6	45.5	9.1	31.8	13	53.8	46.2			34.4	89.5	10.5
SH-1308													
2.5-7.5	22	18.2	31.8	9.1	40.9	12	66.6	33.4			38.4	84.4	15.6
36-40	18	16.6	44.4	27.7	11.1	—	—	—			32.0	97.5	2.5
SH-1323B													
16.5-18.5	35	2.9	42.9	—	—	14	57.1	42.9			36.0	94.4	5.6
37-39	18	5.5	83.3	11.1	—	20	40.0	60.0			35.2	95.5	4.5
43-44	24	—	50.0	20.8	29.2	16	50.0	50.0			35.2	93.2	6.8
SH 1315													
3-7						8	50.0	50.0			37.0	87.6	12.4
19-21						20	70.0	30.0			39.2	88.8	11.2
30-32						14	50.0	50.0			36.8	87.0	13.0

Calcium : As would be expected in carbonate rich sediments such as the bulk of those analysed here, calcium is largely present as calcium carbonate soluble in acetic acid. However, in most of the samples analysed, some smaller fractions of it is present in other phases of the sediments.

The data presented here facilitate discussion of the sources of the elements determined to western equatorial Indian Ocean Sediments. A recent study on the mineralogy of surface sediments from the Arabian Sea by Kolla, Kostecki, Robinson and Biscay (1981) has highlighted the main sedimentary origins of the non-carbonate deposits in that region. All but one of the cores described in the present work were obtained from just to the south of the area considered by Kolla, Kostecki, Robinson and Biscay (1981), but, based on information on their nearest samples, would appear to be beyond the influence of local terrigenous sources of elements. Smectite, quartz, chlorite and palygorskite of continental derivation are all low in the northern equatorial belt of the western Indian Ocean and illite and kaolinite of distant continental derivation appear to be the main clay minerals present.

It is evident from the data given in the present work that there is a variability in the cores described. The core from the Arabian Sea for example, is different from the Somali Basin cores, which also show some differences among themselves. However, not only are bulk compositional variations observed between the cores, but there are variations in their partition characteristics too. Manganese for example, which is normally present in the form of acid reducible ferromanganese oxides in the sediments is both considerably reduced in average abundance in core 1323 A relative to its content in most of the other cores and what little Mn that is present is largely in the acetic acid soluble fraction. Likewise in core 1318, Mn is again much lower than average and again only a minor part of it is present in the acid reducible fraction, but unlike in core 1323A, the bulk of it is not associated with the acetic acid soluble fraction. The single largest portion of the Mn in this core is in the HCl soluble fraction. Similarly, Ni is present largely in the HCl soluble fraction of the sediments in core 1300 from the Arabian Sea whereas in the Somali Basin cores, it tends to be more evenly partitioned between the different fractions of the sediments or concentrated in the HCl insoluble residue or in the acetic acid soluble fraction. Geochemical variations such as these reflect differences in the nature of the constituents supplied to the different sediments, and will be considered in more detail below :

In order to gain some insight into possible terrigenous sources of supply of elements to the sediments described here, the geochemical data obtained in this work have been compared with data on sediments from the western margin of the Indian sub-continent. These sediments are mainly terrigenous in origin (Kolla, Kostecki, Robinson and Biscay, 1981), and if they contain a substantial aeolian component could be taken to reflect the composition of at least part of the terrigenous component of the deep sea sediments considered here, even though all the terrigenous material in the present cores may not necessarily have been supplied from the same source as in the Indian continental margin sediments. No comparable data are available on

Table IV. Ranges and average concentrations of various elements in the sediments of the western continental shelf on bulk samples basis and carbonate free basis.

	A		B	
	1	2	1	2
Al%	0.02-10.9	0.17-11.94	4.44	6.04
Fe%	0.38-7.73	2.25-12.72	4.26	6.52
Ti ppm	500-11500	2700-11200	4200	6600
Mn ppm	27-1466	128-3895	491	766
Ni ppm	19-365	21-744	90	146
Cu ppm	6-218	25-575	90	156
Zn ppm	2-158	11-366	6	105
Co ppm	3-57	3-766	22	55

A (1) Range of values in the bulk samples.

(2) Range of values on carbonate free basis.

B (1) Average value in the bulk sample.

(2) Average value on carbonate free basis.

Table V. Average concentrations in the Indus shelf and western continental slope sediments.

Elements	Indus Shelf Sediments		Western Continental slope sediments	
	Bulk Sample	Carbonate Free Basis	Bulk Sample	Carbonate Free Basis
	1	2	1	2
Fe	3.69%	4.88%	3.19%	5.82%
Mn	5.43 ppm	720 ppm	2435 ppm	4542 ppm
Ti	0.37	0.47%	0.35%	0.59%
Ni	107 ppm	173 ppm	168 ppm	303 ppm
Cu	43 ppm	55 ppm	91 ppm	181 ppm
Zn	201 ppm	252 ppm	206 ppm	395 ppm

African continental margin sediments which can be used for comparison, nor have shipboard samples of aeolian dusts been collected from the region. (Chester — personal communication, 1983).

A good deal of information is available on the distribution of CaCO_3 and elements such as Al, Fe, Ti, Mn, Ni, Cu, Co and Zn in the sediments of the western continental shelf and slope of India, and of the Indus shelf (Marchig, 1972; Rao, Rajamanickam, Murty and Reddy, 1976; Rao and Setty 1976; Murty, Rao, Paropkari and Topgi, 1978; Rao, 1978; Borole, Sarin and Somayajulu, 1982). Average concentrations of elements computed from these cited literature in surface sediments from (i) the western continental shelf of India, (ii) the Indus shelf and (iii) the north western continental slope of India are given in Table IV & V. Comparison of these average values with that of the data obtained in this work (Table I, IV & V) shows a number of features of interest, as detailed below:

With respect to the western Indian continental shelf sediments, on a bulk sample basis, there is considerable enrichment of Mn in cores 1300, 1305, 1313 and 1323B, and of Ni and Zn in core 1300. When the data are recalculated carbonate free, the Mn is enriched in cores 1300, 1305, 1306, 1308 and 1313, 1323B, 1315; Zn in cores 1300, 1305, 1308 and Co in cores 1315, 1318 and 1323B. There are no enrichments of other elements in the present cores relative to those from the western Indian continental shelf.

With respect to the Indus shelf sediments, on bulk sample basis, Mn is enriched in cores 1300 and 1305 and Cu in core 1300. On a carbonate free basis, Mn is enriched in all the cores except 1318 and 1323 A, Cu in all the cores except 1315 and 1323A, and Ni in 1315, 1318 and 1323B. There is practically no enrichment of Fe, Ti and Zn in the deep sea cores relative to Indus shelf sediments.

On bulk sample basis, there are no enrichments of any of the elements determined in the present cores relative to their values in sediments from the western continental slope of India. However, on a carbonate free basis, Mn is enriched in cores 1315 and 1323B and Cu in cores 1305, 1306, 1300 and 1313.

It is evident from these comparisons that the elements Fe, Ti and Al are not enriched in any of the deep sea cores relative to the Indian continental margin sediments. As mentioned, the non-carbonate fraction of the latter has been shown to be largely lithogenous in origin (Kolla, KostECKI, Robinson and Biscay, 1981) and thus lithogenous sources probably also supply much of the Fe, Al and Ti to the present deep sea sediments. This conclusion is borne out in part by partition analyses. Partition analyses also supports a lithogenous source for Fe and Al which are largely concentrated in the HCl soluble and insoluble fractions of the sediments. The partition analyses, which show that although Ti has a variable partition from core to core and it is predominantly associated with the HCl soluble and insoluble phases, supporting its proposed lithogenous association.

In contrast to Fe, Ti and Al, manganese is enriched to a greater or lesser extent relative to the Indian continental margin sediments on a carbonate free basis in most of the deep sea cores studied here. This suggests a source of manganese in these sediments additional to lithogenous sources. This supposition is confirmed by the partition analyses, which shows most of the manganese to be present in the acid reducible fraction in which it will occur as authigenic ferromanganese oxides. Even where the bulk of the Mn is present in the acetic acid soluble fraction of the sediments, as in core 1323 A, it is probably still largely present in ferromanganese oxides as coatings on carbonate tests, although some substitution in the carbonate lattice is also possible.

Other elements exhibit a rather variable behaviour between the different cores studied. Ni, for example, is only enriched in some of the cores relative to western Indian continental shelf and Indus shelf sediments and not at all relative to the Indian continental slope sediments. This seeming lack of a non-lithogenous Ni enriched phase in most of the sediments is borne out by the

partition analyses which shows that Ni is not contained to any appreciable extent in the acid reducible ferromanganese oxide fraction of the sediments. Its variable behaviour between the cores studied would tend to suggest a background lithogenous source for this element, superimposed on which are variable contributions from other sources from core to core.

Copper tends to be enriched on a carbonate free basis relative to Indian continental margin sediments in a greater number of the present cores than Ni. However, there is no evidence from the partition analyses of it being housed to a major extent in the authigenic ferromanganese oxide phase, suggesting some other non-continental source or sources for this element. Much of the Cu is housed in the HCl insoluble fraction of the sediments, where the background lithogenous contribution of continental derivation may be augmented by Cu contributed by volcanoclastic material derived from within the western Indian Ocean and which could also be supplying a portion of the other elements present. Many of the Somali Basin cores were collected adjacent to a range of volcanic seamounts, thought to be presently inactive but which could supply material to the sediments on alteration and slumping. The significant amounts of Cu associated with the acetic acid soluble fraction of the sediments is likely to be contributed by organic processes.

Unlike the other minor elements, Zn is present in significant proportions in the acid reducible phases of the sediments described here, suggesting that at least part of it is housed in authigenic ferromanganese oxides. However, Zn shows only limited enrichment in the sediments over its contents in the western Indian continental margin sediments and so the likelihood of major authigenic precipitation of Zn is small.

The major geographical differences between the cores occur between 1300 from the Arabian Sea and the remainder. This core is markedly enriched in detrital constituents relative to the remaining cores on a non-carbonate free basis and also differs from most of them compositionally on a carbonate free basis, being high in Fe, Al and Ti. This would suggest that it is receiving a significant terrigenous input, most probably from the Indus River system and adjacent areas (Kolla, Kostecky, Robinson and Biscay, 1981). Significant chemical differences also occur between some of the remaining cores examined in this work. The shallow seamount cores 1315 and 1318 are depleted on a carbonate free basis in Mn, Fe, Al, Ti, Cu and Ni relative to the deeper water seamount cores and those from the Somali Basin.

This may partly be a reflection of the incorporation of volcanic alteration products in the deeper cores which have slumped from the seamounts. Cores 1323A and B, also collected from seamounts but at depths greater than 1315 and 1318 are somewhat depleted in Fe and Cu relative to the deeper water cores, but not to the same extent as 1315 and 1318.

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