

Deep Sea Drilling Project Site 219 on the Laccadive Ridge

H. N. SIDDIQUIE, M. VEERAYYA, CH. M. RAO, P. S. N. MURTY & C. V. G. REDDY

National Institute of Oceanography, Dona Paula 403004

Received 23 January 1976

Deep Sea Drilling Project Site 219 on the Laccadive Ridge penetrates Pleistocene to upper Paleocene sequence. A re-examination of Unit V (upper Paleocene) indicates that the Unit consists of rhyolitic tuffs and limestones. Fragments of tuff and broken grains of feldspar in the overlying limestones suggest that explosive volcanic activity continued in nearby areas till about lower Eocene. Acidic tuffs of similar age also occur on the West Coast of India in the Deccan Traps. Lower parts of Unit V are characterized by low percentages of calcite and quartz and the rocks in this unit contain high percentages of montmorillonite and **plagioclase** with minor amounts of clinoptilolite. The overlying biogenous sediments of Units IV, III, II and I are largely marked by high calcite content. Heavy mineral assemblage represents 2 different components : a **terrigenous** component containing hornblende, garnet, zircon, monazite, kyanite, sillimanite, epidote, etc., and an authigenic component containing **glauconite**, anatase, **collophane**, etc. The authigenic assemblage marks the dominantly volcanic sediments and rocks of Unit V and lower part of Unit IV whereas the terrigenous assemblage is associated with the overlying biogenous sediments. The chemistry of the sediments indicates higher concentrations of iron (max: **8.06%**), titanium (max: **1.43%**) and manganese (400-1800 ppm) in the lower parts of Unit V. Mineralogical and geochemical data also support the dominantly volcanic nature of lower and middle parts of Unit V. Major lithological and mineralogical differences in the sediments of the Site are related to the tectonics and sedimentary history of the Laccadive Ridge itself. The culmination of the volcanic activity followed by the subsidence of the ridge to about 2000 m depth marks the change from the volcanic rocks and volcanogenous sedimentation to biogenous sedimentation. When the ridge started subsiding in lower Eocene, shelf edge conditions prevailed briefly at the site and this led to the formation of phosphorite and manganese rich sediments possibly from **upwelled** waters. The eruption of Deccan Traps was followed by extensive faulting on the Western Continental margin of India which formed the **Cambay** Laccadive **graben**. The Deccan Trap and the associated **volcanics** form the basement in this area on which **1.5-5** km thick sediments are deposited from Paleocene onwards. Faulting of the West Coast of India and tertiary uplift of the Western **Ghats** created a slope of the South Indian Peninsula to the east which deprived the **Cambay-Laccadive graben** of large quantities of terrigenous sediments from the East particularly in the Central and Southern areas and favoured deposition of biogenous and chemogenous (carbonate) sediments in this area till recent times. The Laccadive ridge therefore would have exercised considerable influence in separating distinct sedimentary **facies** in this region.

DEEP Sea Drilling Project during Leg. 23A has drilled 6 sites in the Arabian Sea. Of these sites, site 219 is the nearest to the Indian subcontinent and, therefore, of considerable interest to Indian geologists. The site ($9^{\circ}01.75'N$, $72^{\circ}52.67'E$) is situated on the Laccadive-Chagos Ridge in the 9" Channel (Fig. 1). The site is drilled in a water depth of 1764 m, and a penetration of 411 m achieved. The hole has penetrated a stratigraphic sequence ranging from upper Paleocene to Recent. One of the authors (HNS) has participated in this Leg and the results of the drilling in the Arabian Sea have already been published^{1,2}. The present paper is based on the work carried out on the samples collected from site 219. The investigation includes studies of thin sections, clay mineralogy, heavy minerals and geochemistry. The work forms part of a detailed study of samples undertaken by the authors from some sites in the Arabian Sea.

Lithology

The Shipboard Scientific Party divided the section drilled at site 219 into 5 units. Though the stratigraphy of the site has been described earlier², these are being re-described as additional laboratory studies have led to elaboration of description in some cases and changes in the description of others particularly Units IV and V (Table 1, Fig. 2).

Unit I - Almost the entire unit consists of detrital silty clay nanno ooze [in describing the units the sediment classification adopted by the Deep Sea Drilling Project has been used] becoming detrital silty clay rich nanno ooze in the lower part. The sediments are of all varied shades of gray except for a thin olive brown bed in core 219-1-3-130-150 cm. Detrital percentage varies from 20 to 48 while nanno fossils are more than 55% and calcium carbonate ranges from 42 to 76%. The upper 15 m showed on an average

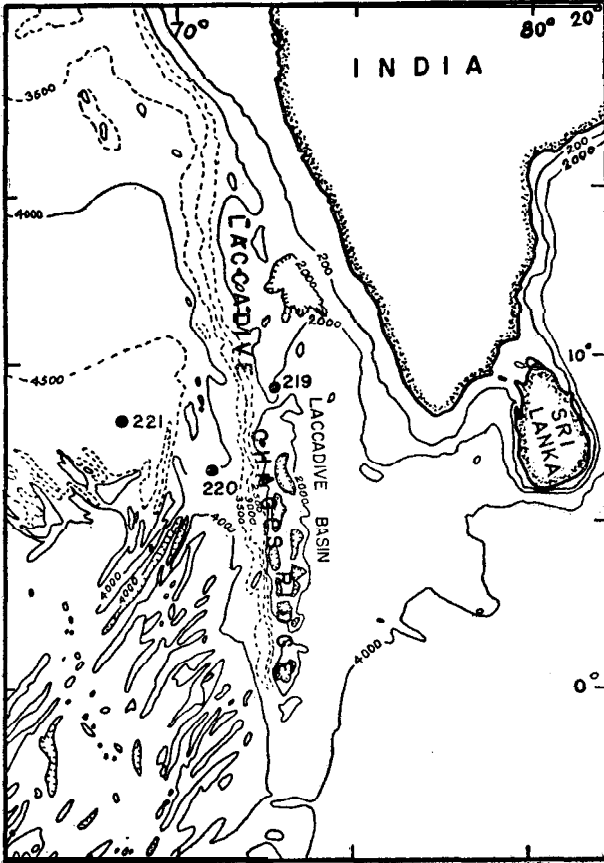


Fig. 1 — Location of Site 219 on the Laccadive Ridge [Depth contours in metres. Map based on Whitmarsh *et al.*²]

TABLE 1 —DEPTH, THICKNESS AND CORES OF DIFFERENT LITHOLOGICAL UNITS AND THEIR SUBUNITS

Unit	Subunit	Depth (m)	Thickness (m)	Cores
I		0-120	120	1-13 (1) 13 (1)-14
I::	a	146-165	Ca26 23	15
	b	165-178	13	16-17 (1)
	c	178-204	26	17 (2)-20 (2)
IV	d	204-219 219-300	15 81	20 (3)-21 219-22-28
	V	300-327 327-365 365-411	27 38 46	219A-1-2 219A-3-6 (1) 219A-6 (2)-10 (2) 219A-10 (3)-14

lower percentage of calcium carbonate and considerable fluctuation in values probably related to the changes in the detrital content. The Upper 15 m and the lower 30 m are foraminifera rich (about 15%). Volcanic glass apparently fresh is common in the upper 35 m but does not exceed 5%. Attempts to date the glass by using fission track techniques were not successful because of the very low density of tracks. The low density

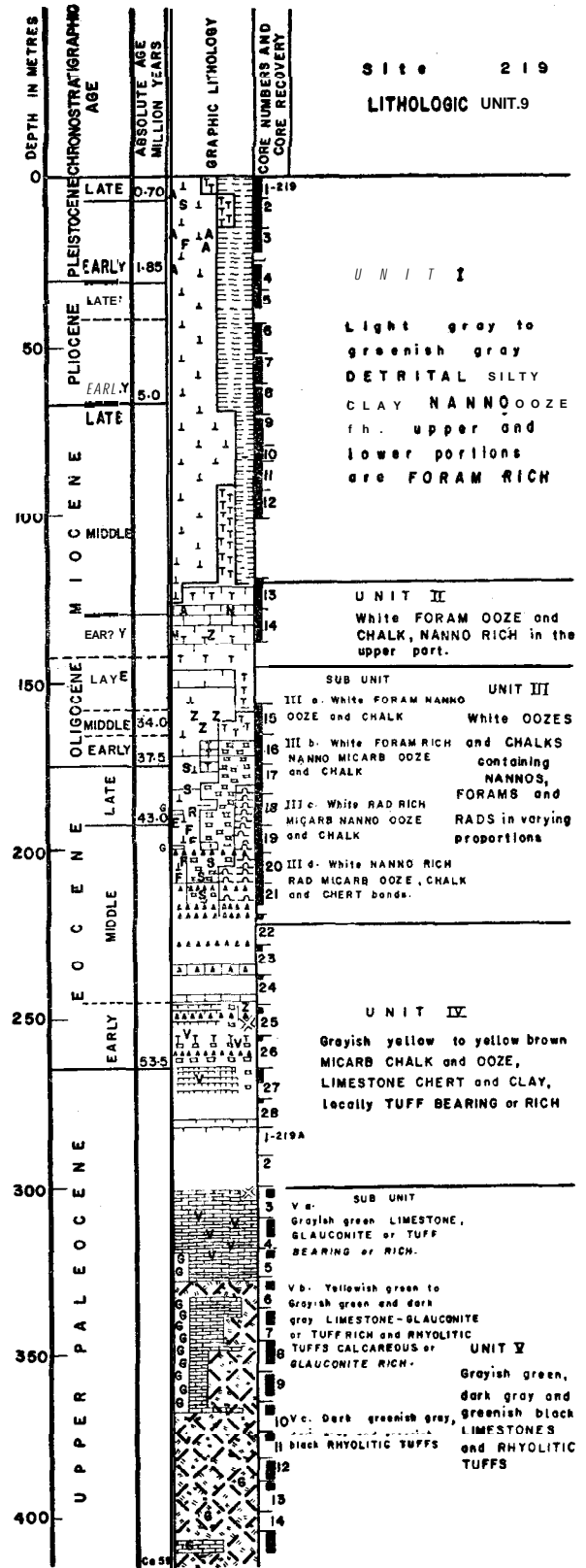


Fig. 2 — Site summary showing lithologic units, ages, depth and core recovery at Site 219

may possibly be due to very low concentration of uranium and or the glass is too young³.

Unit II - This unit is characterized by white nanno rich foram chalk and ooze in the upper part and foram chalk and ooze in the lower part. In the upper part the percentage of nannos varies from 5 to 40 while that of foraminifera vary from 90 to 98%. Calcium carbonate varies from 83 to 93%. The change in lithology from Unit I to Unit II is marked by a fairly abrupt change in colour from gray to white and almost the complete absence of detrital minerals and sudden increase in foraminifera. Thin sections of the foram chalk from the lower part of the unit show very closely packed forams, almost all the shells are intact with a marked paucity of fragments. Minor amounts of coarse fragmental material mostly derived from foraminiferal tests fills the chambers and pore spaces. Very fine-grained carbonates, some of these probably recrystallized fill the pore spaces and in some cases appear to serve as the cement.

Unit III - This 73 m unit consists of white oozes and chalk which contain some thin chert bands. The unit has been subdivided into 4 sub-units.

Sub-unit IIIa: It is characterized by foram nanno ooze and chalk which is locally zeolite bearing. Nannofossils form up to 65%, forams about 13 to 35% of the sediments and minor amounts of micarb also occur. The samples analysed from the sub-unit indicate 84 to 92% of calcium carbonate. Thin sections of the chalk in the lower part of the sub-unit show this to largely consist of foraminifera dispersed in significant amount of fragmental material. The chalk shows distinct layering and stratification and the proportion of fragmental material is comparatively higher than in the overlying formation. Fine grained carbonate fills the pore spaces and serves as the cement also.

Sub-unit IIIb: It is a white foram rich nanno micarb ooze and chalk. The 2 samples analysed from this sub-unit contained 92 and 87% calcium carbonate.

Sub-unit IIIc: This unit consists of white rad rich nanno micarb Goze and chalk, some glauconite also occurs in this unit. In the upper portion of this sub-unit the composition is as follows, foraminifera (5-25%), micarb (20-65%), nannofossils (15-60%), zeolite (trace to 10%), radiolaria (5-20%) and sponge spicules (2-8%). Both the radiolaria and sponge spicules increase towards the lower portion of the sub-unit. A decrease in siliceous organisms from 15 to 5% between cores 19-5 and 19-6 is accompanied by chert formation and development of up to 8% zeolites, the chert beds are thin and occur sporadically. Calcium carbonate in this unit ranges from 65 to 85%.

Sub-unit III d: It consists of white nanno-rich rad micarb ooze, chalk and chert. Many thin layers of chert occur in this sub-unit and coupled with abundant radiolarians gives the sub-unit a siliceous aspect. In this part, nannos range from 15 to 20%, radiolaria 20-25%, micarb 40-55% and sponge spicules and forams about 5% each. The calcium carbonate content varies from 55 to 72%.

Unit IV - The unit consists of hard and soft formations and the core recovery was poor. The hard streaks consist of thin yellowish green chert and limestone. The soft sediments which are more prevalent than the hard ones consist of nanno ooze, foram chalk, micarb foram ooze and chalk and zeolite micarb rich form chalk. The unrecovered section from this unit probably represents the soft sediments washed away during drilling of hard streaks. Thin sections of foram chalk from core 25 (219-25-1-138-140 and CC) were studied. The two differ significantly, the former consists mainly of foraminiferal tests without infilling either in the chambers or in the pores. The infilling material (micarb or glauconite) could have been removed during section making. In some of the tests, fine grained carbonates have filled the chambers, while in some others larger grains probably recrystallized and of a later date also occurs. The intervening pore spaces are filled by fragmentary material. Thin section of material from the core catcher shows foraminifera, carbonate fragments (micarb) and tuffaceous material. Foraminifera are the predominant component, most of the tests being filled with micarb and glauconite. Small pellets of glauconite are also distributed in the rock. Cementing material largely appears to be fine-grained carbonate while some larger grains of carbonate may have precipitated later. Most of the tuff fragments are angular, though some rounded fragments are also seen. Some of the margins may be chilled as evidenced by the occurrence of light green palagonite. The glass varies in colour from clear and greenish to dark black or pitch dark. The telspars in some of the fragments are aligned giving the appearance of layering and flow structure. The felspar grains are largely fresh, sharp and angular indicating the absence of substantial transport and in turn the nearness of the source of volcanic activity. In addition other sharp large devitrified grains of glass with angular outline and chilled (?) dark margin are also seen. Some phosphate (?) grains noticed in the thin section may indicate erosion of older rocks containing phosphate in nearby areas.

The material recovered in core 26 was badly fragmented and most of the phosphate was recovered as grains. Because of this it is difficult to study the relationship of this granular material with the host rock (chalk). X-ray analyses of the phosphate (by Dr B. B. Mukherji) indicated this to be mainly apatite (carbonate apatite). Thin sections (219-26-1-17-19) however show 3 different modes of occurrence (i) bedded, (ii) minute grains distributed along the bedding of rock and (iii) replacement of foraminiferal shells. Sections of bedded phosphate are rather rare and the bedding may largely be due to compositional difference. Phosphorite grains distributed along the bedding are rather common. A number of foraminifera occur in the phosphate and these show various stages in the replacement of carbonate (calcite or aragonite forming foraminiferal tests) by phosphate. It is very likely that the original sediment contained comparatively larger proportion of shells many of which have been entirely replaced by phosphate. The examination

of the thin section shows that the replacement of calcite in the foraminiferal tests started through the pores in the radial hyaline calcite crust. Microgranular hyaline inner layer of the outer wall was the first to be replaced, finally in advance stages the septal walls, and subsequently even the outer radial walls have been almost completely replaced

and only minute traces of calcite grains represent the outline of the replaced shells (Fig. 3).

Unit v - The rock types in the unit show considerable variation. The unit has been tentatively subdivided into the following 3 sub-units.

A major change in the description of this unit⁴ from the earlier one by the Shipboard Scientist⁹

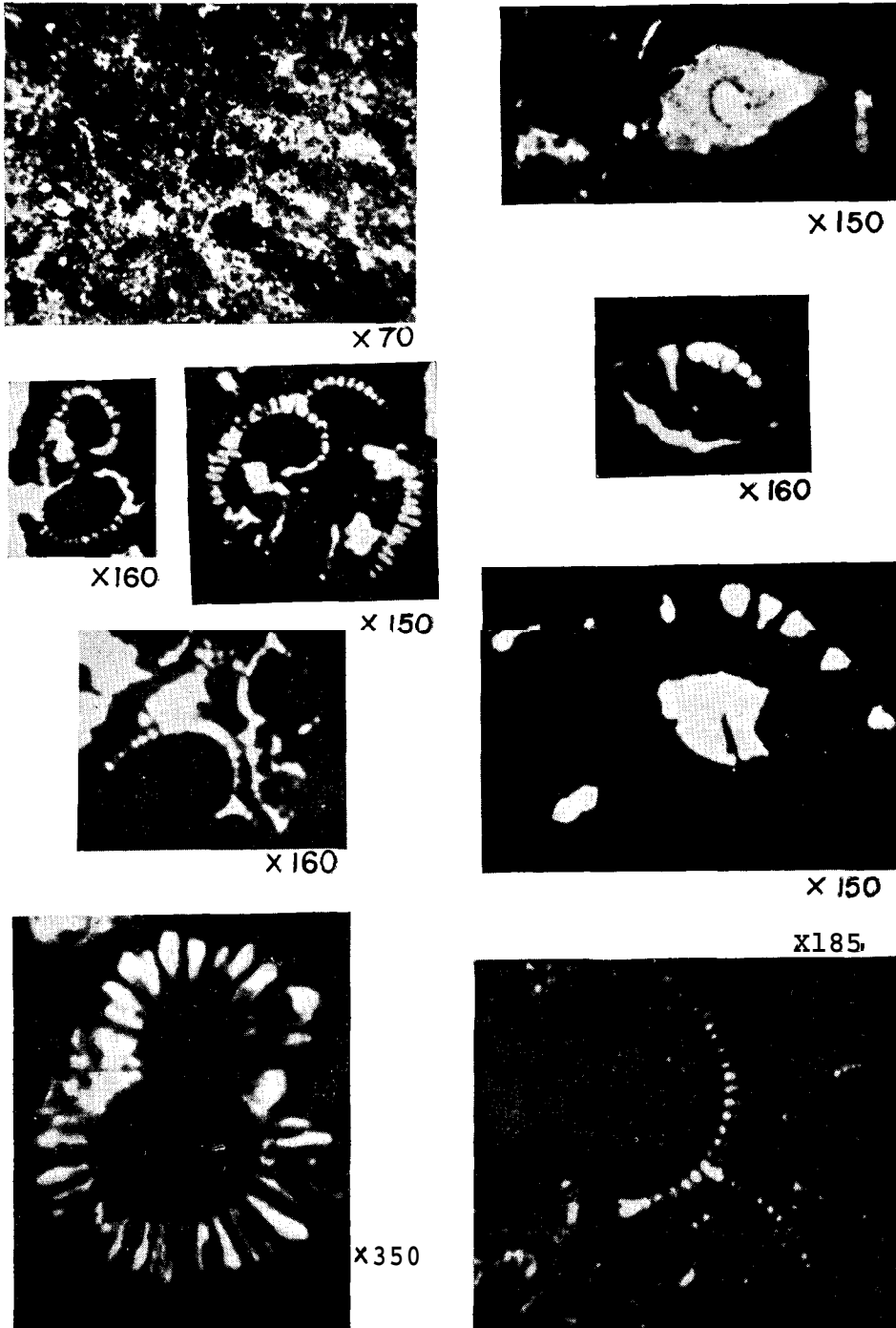


Fig. 3 — Phosphate in the micarb chalk of 219-26-1-17-19 [Top left hand corner shows phosphates occurring in the micarb chalks. The other photomicrographs show various stages in the replacement of foraminifera by phosphates

is the identification of acid felspathic and rhyolitic tuffs. Some of these tuffs may also contain re-worked material derived by volcanic activity in nearby areas. Some of the rocks of Unit V appear similar to the description given for the Paleocene-Lower Eocene, Trap wacke, sand silts and claystone of the Cambay basin by Raju⁵ and matrix of the conglomerate in the Balutri formation by Roychoudhury *et al.*⁶. A re-examination of the cores with more closely spaced thin section may improve the description and classification of this unit.

Sub-unit Va: It consists of grayish green limestone. The limestone contains forams and molluscan shell fragments, some of the layers show burrow structure and cross lamination etc. Part of the sequence contains glauconite or tuff in varying proportions and the calcium carbonate ranges from 63-88%. Thin sections of the rocks from this sub-unit indicate differing composition. A section from the top of the sub-unit (219A-3-2-27-28) largely consists of carbonate fragments with minor amounts of feldspar and tuffaceous fragments. Another section from the same barrel (219A-3-2-119-120) consists of foraminifera and other shells with a comparatively large content of shell fragments, some large calcite grains may have been precipitated later. The grains have been cemented by very fine grained carbonates.

Sub-unit Vb: This unit consists of yellowish green to grayish green and dark green limestone and rhyolitic tuffs, the former are glauconite or tuff rich while the later is calcareous or glauconite rich. The calcium carbonate varies from 3.5-58%. Some of the layers are rich in shell fragments, pelyceps, forams, ostracods, red algae, bryozoans and belemnites. The sub-unit represents an admixture of both biogenous and volcanogenous sediments and a detailed examination may reveal alternate limestone and tuff beds. A thin section (219A-6-2-34-35) examined from this sub-unit shows a fine grained rock with needles and phenocrysts of feldspar (albite/oligoclase) and perlitic glass. The rock has a distinct igneous texture and may be called acidic or rhyolitic tuff. The underlying rocks in barrel 8 and 10 from which some thin sections were examined appear to range from tuff or glauconite bearing to rich limestones. This variation is also reflected in the analyses for calcium carbonate. The limestones contain fairly large feldspar crystals some of these are broken and many are oriented along the flow.

Sub-unit Vc: Except some shelly horizons in barrel 14, it almost entirely consists of rhyolitic or felspathic tuffs. The calcium carbonate content is generally low and ranges from 1 to 10.6% but rises in the shelly horizons to even 41%. The rocks show distinct igneous texture with feldspar needles as well as large phenocrysts distributed in glass.

Studies of Sediments and Rocks

Samples from various stratigraphic units were studied for mineralogy (X-ray analysis and heavy

minerals) and geochemistry. The results of these studies are described and discussed below.

Mineralogy

X-ray-X-ray analyses of 48 samples have been carried out at the Riverside Laboratory of Deep Sea Drilling Project (semiquantitative analysis) and at the Geological Survey of India (qualitative analysis). The analysed samples include bulk, 2-20 μ , less than 2 μ and acid treated fractions drawn from various stratigraphic units (Table 2). The analyses provide a fairly representative coverage of the stratigraphic column at the site.

X-ray analyses of the untreated bulk, 2-20 μ and even the <2 μ fraction indicate that calcite is the major mineral in most of the samples except in Unit V where montmorillonite is dominant. High calcite content of sediments of Units I to IV is due to the large contribution of biogenic material. Dolomite is the only other carbonate and occurs in small quantities (0.9%) in Unit I only. Quartz occurs in traces in all the samples analysed except those from Unit V where it is not reported. Particularly high content of quartz is reported in Unit I which is obviously related to the high percentage of detrital material. K-feldspars are reported from Units I and II and this may be related to the high percentage of detritals particularly in Unit I. Plagioclase is reported in samples from all the units but particularly higher percentages are noted in Unit V (2-43%). Higher concentration of plagioclase particularly in Unit V is associated with high concentration of montmorillonite as also some clinoptilolite and the 3 minerals may have the same source.

Among the clay minerals illite/mica (trace to 30%) and minor amounts of kaolinite and chlorite occur only in Units I and II. Kaolinite is reported in association with K-feldspar indicating that the source of the 2 minerals may be the same. Polygorskite is reported from a sample in Unit II and is in significant quantities to be recorded even in bulk samples. Montmorillonite occurs throughout the stratigraphic column in trace or as a major component. Particularly in Unit V it is the most important mineral even in bulk samples, accounting for 49-60% in 2 of the bulk samples and the major or main component and over 90% of the less than 2 μ fraction of many samples. It is associated generally with plagioclase (2-43%), traces of clinoptilolite (though in one case it is as high as 42%) and presence of phillipsite. The other non-clay minerals in Unit V are pyrite and anatase.

The mineral distribution in the entire column shows that 2 distinct mineral assemblages can be demarcated. Sub-units Vb and Vc are marked by low percentage of calcite and quartz and the sediments and tuffs in these sub-units almost entirely consist of montmorillonite, with a high percentage of plagioclase and in some cases clinoptilolite and phillipsite. Montmorillonite usually indicates a volcanic origin, its association with large amounts of plagioclase and significant amounts of clinoptilolite and phillipsite confirms this.

TABLE 2 — X-RAY ANALYSES OF SEDIMENTS AND ROCKS FROM SITE 219

Hole	Barrel	Section	Horizon c m	Fraction μ	Quartz	Plagi- clase	K Fels- par	Maj	Calcite	Dolomite	Kaolinite	Mont- morillo- nite	Mica	Illite	Chlorite	Poly- gorskite	Anal- cite	Clinopti- lolite	Phillip- site	Anatase	Halite	Pyrite
219	2	5	113-115	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	3	1	100-102	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	6	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	6	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	8	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	8	2	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	9	1	45-47	Bulk	3.6	1.2	—	90.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	9	1	45-47	2-20	46.7	19	12.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	9	1	45-41	<2	13.3	1	2.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	10	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	10	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	12	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	12	2	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	13	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
13	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
14	5	5	Bulk	3.6	—	—	90.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
14	5	5	<2	12.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
15	5	5	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
15	5	5	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
16	6	6	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
16	6	6	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
18	1	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
18	1	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
18	1	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
19	6	6	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
21	2	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
21	2	2	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
25	1	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
26	1	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
26	1	1	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
27	1	1	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
27	3	3	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
27	3	3	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
219A	3	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4.1
	5	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8.3
	5	2	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	5	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	5	2	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	5	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	7	3	3	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	8	2	2	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	10	10	10	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	11	11	11	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	11	11	11	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	11	11	11	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	13	13	13	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	13	13	13	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
13	13	13	120-122	<2	tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
14	14	14	120-122	<2	at tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

The overlying sediments (219A barrel 4 and above) with their large carbonate content (due to foraminifera and calcareous nannos, etc.) are dominantly biogenous sediments. Montmorillonite occurs throughout these sediments as traces or even as a major component in the clay fraction. In Unit II this may be related to volcanic activity (lower Miocene?) in the nearby areas as indicated by occurrence of volcanic glass. Though volcanic glass also occurs in the Pleistocene sediments (Unit I) of this site but no montmorillonite occurs, Goldberg and Griffir's⁸ analyses of clay minerals in the recent surface sediments of the northern Indian Ocean indicated that a belt of sediments with 50-70% montmorillonite surrounds the Indian subcontinent and evidently these are derived from the Deccan Trap region. Montmorillonite in the sediments of Site 219 (barrel 4-219A and above) has been derived from the Deccan Trap region on peninsular India and these small quantities have been transported to the Laccadive ridge as suspended matter or eolian dust. Sporadic occurrence of kaolinite and K-felspar together in some samples from Units I and II indicates derivation from a similar source probably acid igneous for part of the sediments in these Units.

The major lithological and mineralogical differences in the sediments of the site above barrel 5 (219A) are related to the tectonic and sedimentary history of the site and the Laccadive ridge itself. It is well known that montmorillonite is largely derived from volcanic rocks and therefore the sediments and rocks of Unit V (Paleocene) are predominantly of volcanic origin. The Deccan Traps are regarded as Cretaceous to Eocene, the tuffs and the associated sediments may represent a manifestation of the extensive Deccan Trap activity on the Laccadive Ridge itself. The decrease in montmorillonite concentration above barrel 4 (219A) is evidently due to the culmination of volcanic activity at the site. Minor amounts of montmorillonite in the overlying sediments associated with volcanic tuff pieces in sub-unit Va and Unit IV indicate that though volcanic activity ended at this ridge evidently it continued in nearby areas which provided the tuff fragments and montmorillonite to the overlying sediments. With further tectonic movements and subsidence of the ridge in early Eocene (barrel 26-219 and above) the site passed to deep sea environments. Subsequently with the deepening in early Eocene and formation of the Laccadive Sea, dominantly biogenous carbonate sedimentation continues till today at the site.

Heavy minerals — Heavy minerals from some of the samples were studied to decipher the provenance of sediments, particularly if any of the sediments have been derived from peninsular India to the east. Heavy minerals were separated from 20 samples but in almost all the cases recovery was poor. The samples were first disaggregated and dispersed in water and washed in 230 mesh ASTM sieve to separate the coarse fraction. The coarse fraction was treated with bromoform to separate the heavy and light fractions. Part of the material was treated with dilute hydrochloric acid to remove stains and subsequently treated

TABLE 3 — HEAVY MINERALS FROM SEDIMENTS AND ROCKS FROM SITE 219

(Values expressed in per cent)

Sample No.	Total No. of grains	Hornblende	Tourmaline	Zircon	Monazite	Augite-Diopside	Epitrite	Kyanite	Sillimanite	Garnet	Collophane	Glaucophane	Barite	Anatase	Muscovite	Glass	Unidentified	Rock fragments	Apatite
219/2/5/113-115	15	33.3	—	—	—	—	—	—	—	—	—	—	—	—	12.4	—	24.4	—	—
219/8/2/120-122	65	86.1	—	—	—	—	3	—	—	—	—	—	—	—	7.7	—	—	—	—
219/21/2/120-122	222	91.4	0.9	—	—	—	1.3	—	—	0.9	—	—	—	—	2.2	3	0.4	—	—
219/25/CC	283	40.2	0.3	0.3	0.3	—	0.7	1.7	—	2.1	0.7	—	3.9	46.6	2.8	—	—	—	—
219/26/1/135-137	153	11.7	—	3.9	—	—	2	0.6	—	—	2.6	—	1.3	77.8	0.6	—	—	—	—
219A/3/1/139-140	16	56.25	—	—	—	—	—	—	—	6.25	18.75	—	—	18.75	—	—	—	—	—
219A/3/2/27-28	55	34.5	1.8	—	—	—	—	1.8	3.6	20	3.6	—	—	29	1.8	—	—	—	1.8
219A/3/2/117-120	71	62	—	—	5.6	—	2.1	1.4	—	8.4	—	—	—	18.3	—	—	1.4	—	—
219A/4/2/80-83	46	—	—	—	—	—	—	—	—	2.2	—	69.6	—	28.3	—	—	—	—	—
219A/4/2/124-125	70	8.6	—	1.4	2.8	—	—	—	—	18.6	—	12.8	2.8	11.4	10	—	—	27.1	—
219A/4/3/60-62	69	31.9	—	—	4.3	—	2.1	—	—	8.7	—	13	—	14.5	2.9	—	—	21.7	—
219A/5/2/117-120	20	45	—	—	—	—	—	5	—	5	—	—	—	40	5	—	—	—	—
219A/6/2/34-35	29	10.3	—	—	—	—	—	—	—	3.4	—	17.2	—	65.5	—	—	—	—	—
219A/8/3/56-57	170	13.6	—	—	—	—	—	—	—	28.2	2.3	2.3	5.9	44.1	—	—	—	—	—
219A/8/5/22-23	40	15	—	—	—	0.6	—	—	5	2.5	—	20	—	57.5	—	—	—	—	—
219A/10/2/127-128	32	6.2	—	—	—	—	—	—	3.1	12.5	—	—	—	78.1	—	—	—	—	—
219A/11/2/82-83	143	54.2	—	0.6	—	—	—	—	—	7	—	—	—	30.8	1.4	—	—	—	—
219A/14/3/138-140	59	40.7	—	3.4	—	—	—	—	—	16.9	6.8	—	6.8	13.5	3.4	—	—	—	—

with bromoform to separate heavy and light minerals. All the minerals in the slide were counted and the results are given in Table 3.

The heavy mineral assemblage is characterized by hornblende, garnet, anatase, glauconite, collophane, kyanite, epidote, zircon, mica and barite etc. Some of the heavy minerals are described below.

Hornblende: Hornblende occurs (5-91%) in all the samples studied. Hornblende in the samples studied is darkgreen to brown in color with well defined cleavage. The percentage of hornblende is comparatively high in the samples from Units I, III and IV and low in those of Unit V.

Garnet: Garnet ranges up to 29% and is particularly prominent in the samples from Unit V. Garnet in these samples is colorless, angular but some of the grains are pitted and etched. Brown and green colored grains are also found but these are rare.

Anatase: This mineral is predominant in samples from Units IV and V and ranges up to 77%. The grains are euhedral with well defined prismatic and pyramidal faces, most of the grains are colorless, but some have a bluish tinge.

Glauconite: It is only recorded in the samples from lower parts of sub-unit Va and in sub-unit Vb and ranges up to 20%. Glauconite in these sediments is greenish and occurs as rounded pellets and aggregates or irregular grains.

Minor amounts of kyanite (up to 1.8%) occur in some of the samples. The grains are colourless, clear and in some cases with well rounded edges. Sillimanite also occurs in some of the samples. Solitary, clear and euhedral grains of zircons have been noted in the heavy minerals of most of the slides. Undoubted typically rounded and colourless grains of monazite with characteristic birefringent rings have been noted in some of the slides. Typical bottle green and greenish yellow grains of epidote occur in the samples and range up to 7%. The heavy mineral assemblage especially in lower parts of Unit IV contains some minor amounts of collophane. The grains are greenish, rounded and isotropic and may represent replacement of hard parts of some organisms by phosphates. The heavy mineral assemblage in the samples below 25 cc (219) show some euhedral crystals which have been provisionally identified as barite.

The heavy mineral assemblage indicates 2 different components, a mineral assemblage characteristic of terrigenous sources, i.e. hornblende, garnet, zircon, monazite, kyanite, sillimanite, and epidote etc. and the other of authigenic origin, i.e. glauconite, anatase, collophane and barite, etc. These together provide some information about the source rocks and environments of deposition in the area. The terrigenous mineral assemblage largely indicates an acid igneous (plutonic and volcanic) and high rank metamorphic source. The assemblage in the biogenous sediments of Units I to III is largely dominated by hornblende. Hornblende in the heavy minerals is largely greenish brown indicating that the source is dominantly igneous rocks. This coupled with the montmorillonite in the clay fraction of the sediments indicates that the detrital fraction

in these biogenic sediments has a dominantly volcanic source and in all probability these are the Deccan Traps of Peninsular India. Associated euhedral zircon and monazite are typical of the Archaean rocks of South India, the later particularly of some of the rocks in Kerala on the South West coast of India. Their percentage is rather low and such small quantities of heavy minerals have been recorded in the suspended matter and could have even been transported by a similar mechanism from the south Indian coasts. As mentioned earlier the heavy mineral assemblage is characterized by a decrease in hornblende and an increase in garnet in Unit V. Garnets may be a part of the detritals supplied from the South Indian peninsula to the east. The decrease in the garnet in the overlying formation may be due to the subsidence of the Laccadive Ridge and formation of the Laccadive sea which drastically reduced the terrigenous supply from peninsular India to the east. The paucity of hornblende in the sediments of Unit V may be due to the general absence of ferromagnesian minerals in the associated volcanics and possibly in the source areas as well.

Among the authigenic minerals, anatase is the most abundant and it occurs in significant quantities both in Units IV and V. Volcanic activity in the area provided an abundant supply of titanium which led to the precipitation of anatase, particularly in the volcanogenic sediments. The next authigenic mineral in order of abundance is glauconite. Hunziker and Matter⁹ have reported that the mineral is a proto-glauconite¹⁰ and actually montmorillonite or a pectonite variety. The glauconite recorded in the heavy mineral assemblage may be an alteration product of volcanic rocks in the area. The other minerals in this assemblage, are collophane and barite. Minor quantities of collophane occur in Units V and IV, and in both these units these are probably hard parts of organisms replaced by phosphates formed by upwelled waters. The occurrence of barite in these samples, may be possibly either due to volcanic activity or higher productivity in the area during the Paleocene.

Geochemistry

Distribution patterns of some of the elements (Mg, Ti, Mn, Cr, Cu, Ni, Fe, V and Ba) in the sediments of this site were reported by Whitmarsh *et al.*². The studies were, however, based on the semi-quantitative analyses of a few samples from different Units. A detailed study of the elemental geochemistry of these sediments and tuffs was taken up to understand the (i) overall distribution patterns of various elements on the total sample basis, (ii) contributions made by different components of sediments and tuffs to the absolute concentrations of elements in total samples, and (iii) factors and processes of incorporation of these elements in sediments. Distribution patterns of iron, manganese and titanium in 63 samples of sediments and tuffs of site 219 were studied and the results obtained on the total sample basis are presented here.

All the samples were digested with hydrofluoric acid and perchloric acid following the method of Chester and Hughes¹¹ and iron, manganese and

titanium were estimated spectrophotometrically using Unicam SP 500 spectrophotometer. For the estimation of iron and manganese, 2,2'-dipyridyl and potassium periodate were used respectively as described in Sandell²². Titanium was estimated in the samples using the hydrogen peroxide reagent as described by Riley¹³. Calcium carbonate was estimated by the method of Muller¹⁴. Percentage of acid insolubles was estimated by the method of Chester and Hughes¹⁵.

The following generalizations can be made from the data presented here:

(1) Highest concentrations of iron (8.06%) and titanium (1.43%) are encountered in sub-units Vb and Vc while lowest concentrations are in Units II to IV and the sediments of the lithologic Unit I; the upper part of Unit V is having concentrations in between. Highest concentrations of manganese (3463, 864, 8476 ppm) are recorded in samples (219-25-1-108-110, 219-25-1-138-140 and 219-26-1-135-137) but these values appear to be confined to 2 barrels of Unit IV. Sediments and tuffs of Unit V are characterized by a uniformly high concentrations of manganese (442-1823 ppm) and the sediments of Unit II by uniformly low concentrations. Among the other units, sediments of Unit I have relatively higher concentrations of manganese than sediments of Unit III (Tables 4 and 5, Fig. 4). (2) Iron and titanium contents of the sediments in different units broadly follow variations in the percentage of acid insolubles in the respective units. While this is so within the units, although sediments with similar ranges of percentage of acid insolubles are present in the different units, the corresponding ranges of concentrations of iron and titanium are not uniform (Table 6). They vary from unit to unit the trend being one of an increasing one from Unit II to unit V. Manganese content of sediments and tuffs does not show any variations with the percentage of acid insolubles (Table 6). (3) Iron and titanium of sediments in the different units exhibit an inverse relationship with calcium carbonate but manganese does not show any such relationship (Fig. 5). (4) Iron and titanium covary in these sediments but practically there appears to be no significant relationship between these elements and manganese (Fig. 5).

In marine sediments iron may be (i) associated with the lithogenous ferromagnesian minerals (augite, hornblende, magnetite and ilmenite, etc.) of the sediments particularly those containing large amounts of unaltered volcanic material^{16,17}; (ii) incorporated directly from sea water¹⁸; (iii) derived through biological processes^{17,19}; and (iv) associated with the clay minerals either as an essential constituent or as a minor constituent within the crystal lattice or as iron oxide on the surface of the mineral platelet+. Similarly titanium content in the marine sediments may also have several origins. Goldberg¹⁸ suggested that the titanium in pelagic sediments may be of hydrogenous, biogenous or terrigenous origin. According to Correns²¹ titanium may be incorporated in the sediments through the colloidal and suspended matter in the sea water derived from the terrestrial weathering or through residues

from relatively undecomposed terrestrial material and volcanic ash and dust carried by wind and water. Goldberg and Arrhenius¹⁶ found that high titanium contents in pelagic sediments are invariably associated with the presence of basaltic pyroclastics, and in addition to volcanic pyroclastics and manganese nodules, euhedral anatase and rutile are important titanium bearing minerals in the sediments. The origin of manganese supplied to the deep sea has been discussed^{16,18,22-24}. Manganese associated with solids is introduced into the oceans as a result of continental weathering or terrestrial or submarine volcanicity. In addition, there are 3 major pathways by which manganese in solution can reach the oceanic sediment surfaces, viz. continental weathering, volcanic activity and migration from subsurface sediments. Large quantities of manganese are introduced into sea water by hydrothermal solutions associated with sub-marine volcanism²⁴. Some of the manganese thus received is undoubtedly precipitated from sea water, but Graham²⁵ has suggested that stable organic complexes of manganese are formed in the organisms by metabolic processes and these could act as source for manganese in the nodules/sediments. Goldberg and Arrhenius¹⁶ also indicated that biological processes extract manganese from seawater and incorporate into foraminiferal tests and these in turn contribute to the manganese in the sediment. Li *et al.*²⁶ and Price and Calvert²⁷ have provided evidence for the post depositional migration of manganese from the reducing zones and its fixation in the oxidizing zones.

Distribution pattern of acid insolubles in different units shows that sub-units Vb and Vc contain the highest percent age of acid insolubles (48.25-92.25 %). The lowest range of percentage of acid insolubles is in Unit II (5.40-9.75%). Comparatively higher percentage of acid insolubles (20.29-48.2%) is observed in Unit I than in Units III and IV (7.05-35.8 %). Highest concentrations of acid insolubles in sub-units Vb and Vc are due to the dominant volcanic contribution while the next highest concentration in Unit I is due to the large detrital material possibly contributed by suspended material or eolian sources. The lower concentrations in Units II to IV are due to the dominant biogenic sedimentation with relatively lesser contributions from terrigenous sources.

The association of iron, manganese and titanium with the less than 2 μ fraction of sediments of Units I to IV and sub-unit Va can be precluded to a large extent in view of the presence of montmorillonite and or illite in very minute amounts in these sediments. In sub-units Vb and Vc they may in part be associated with montmorillonite which is a major constituent of the less than 2 μ fraction of sediments and tuffs. Pyrite is reported only in some samples and thus the fixation of iron with the sulfide ion in the form of pyrite may be considered purely a local feature. The inverse relation between iron, titanium and calcium carbonate (Fig. 5) suggests that the carbonate phase (mainly biogenic) is not a significant contributor of these elements. The sympathetic relation between the percentage of acid insolubles and the iron and titanium and the linear relation between iron

TABLE 4 -CONCENTRATIONS OF Fe, Mn, Ti, CaCO₃ AND ACID INSOLUBLES IN THE SEDIMENTS AND ROCKS FROM SITE 219

Sample No. (hole, barrel, section, horizon cm)	Depth (m)	Iron (%)	Manganese (ppm)	Titanium (%)	Calcium carbonate (%)	Acid insolubles (%)
219-1-144-46	0.44-0.46	1.22	331	0.19	66.7	20.29
219-1-1-144-146	1.41-1.46	2.16	253	0.27	44.3	41.93
219-1-2-140-142	2.9-2.92	1.83	326	0.26	54.4	33.58
219-1-3-140-142	4.4-4.42	2.41	253	0.31	42.8	40.45
219-1-4-144-146	5.94-5.96	2.59	253	0.28	47.8	42.4
219-1-CC		1.09	253	0.24	57.4	31
219-2-1-72-74	x.72-6.74	1.06	331	0.16	69	20.96
219-2-1-100-102	7.7-02	2.41	230	0.29	45.4	46.19
219-2-2-85-87	8.35-8.37	2.07	270	0.24	55.2	40
219-2-3-60-62	9.6-9.62	2.29	292	0.32	46.4	48.2
219-2-4-100-102	11.5-11.52	1.86	213	0.24	58.4	33.82
219-2-S-10-12	12.1-12.12	2.28	196	0.27	52.6	42.4
219-2-S-113-115	13.13-13.15	1.36	241	0.15	68.6	25.35
219-2-CC	15	2.08	270	0.23	55.4	36.02
219-3-1-100-102	16-16-02	2.44	309	0.29	48.4	46.44
219-3-2-118-120	17.68-17.7	1.49	202	0.19	61.4	30.95
219-3-3-120-122	19.2-19.22	1.73	241	0.23	61.7	30.4
219-3-4-120-122	20.7-20.72	2.53	146	0.26	50	44.22
219-4-1-120-122	25.2-25.22	1.81	286	0.23	60.4	31.55
219-4-2-120-122	26.7-26.72	1.81	213	0.2	60.9	31.52
219-4-3-120-122	28.2-28.22	1.87	219	0.21	57.4	31.93
219-4-4-120-122	29.7-29.72	1.94	241	0.23	60.4	32.99
219-5-1-120-122	34.2-34.22	1.85	298	0.22	59.7	34
219-6-1-120-122	43.2-43.22	2	230	0.23	57.7	31.19
219-7-2-120-1 22	53.7-53.72	1.73	191	0.2	59.6	32.43
219-S-2-1 20-1 22	62.7-62.72	1.34	275	0.16	61	27.22
219-9-1-120-122	70.2-70.22	1.3	185	0.16	61.7	26.66
219-10-1-120-122	79.2-79.22	1.53	287	0.16	62.9	26.7
219-1 1-120-122	83.2-83.22	1.12	196	0.11	71.4	23.55
219-12-2-1 20-122	93.7-93.72	1.23	196	0.13	68.5	27.22
219-13-1-120-122	120.2-120.22	0.09	129	0.09	88.2	7.7
219-14-1-90-92	128.9-128.92	0.43	129	0.029	86.3	7.2
219-14-3-105-107	132.05-132.07	0.12	124	0.036	88.6	5.4
219-14-1-120-122	133.7-133.72	0.13	191	0.04	85.6	8
219-14-5-129-130	135.29-135.3	0.37	123	0.029	83	9.15
219-14-6-15-17	135.65-135.67	0.24	22	0.036	84.2	9.75
219-15-1-5-7	156.05-156.07	0.2	208	0.025	85.6	8.5
219-15-5-100-102	163-163.02	0.2	152	0.038	84	9.2
219-15-5-115-117	163.15-163.17	0.17	181	0.034	81	9.3
219-16-6-70-72	173.2-173.22	0.24	185	0.029	76.8	14.15
219-18-4-40-42	187.9-187.92	0.12	157	0.036	83.6	17.6
219-19-6-100-102	200.5-200.52	0.35	230	0.065	71.2	22.5
219-20-2-120-122	203.7-203.72	0.29	219	0.058	66	29.8
219-21-2-120-122	212.7-212.72	0.52	207	0.059	55.6	35.8
219-25-1-108-110	247.08-247.1	0.55	3463*	0.069	74.8	16.75
219-25-1-138-140	247.38-247.4	0.59	864	0.067	90	14.7
219-26-1-135-137	256.35-256.37	0.67	8476†	0.082	64.8	26.6
219-27-1-95-96	264.95-264.96	0.63	219	0.092	69.8	28.7
219-27-1-148-150	265.48-265.5	0.3	230	0.015	93.4	10.2
219-27-3-90-92	267.9-267.92	0.24	258	0.046	92.4	7.05
219A-3-2-27-28	300.77-300.78	0.59	654	0.081	88.2	9.6
219A-4-3-60-62	311.6-311.62	0.74	1043	0.13	88.6	11.2
219A-5-2-117-120	319.67-319.7	2.19	860	0.14	63.4	26.15
219A-6-2-34-35	327.84-327.85	2.32	896	0.17	73	24.32
219A-7-3-48-49	338.48-338.49	8.06	1274	0.99	32	59.1
219A-8-2-35-40	345.85-345.9	3.77	442	0.39	43.6	48.24
219A-8-5-22-23	350.22-350.23	3.67	581	0.43	15	82.24
219A-10-2-127-128	364.77-364.78	3.67	852	0.49	3.6	90.58
219A-10-3-130-131	366.3-366.31	5.16	1096	0.49	9	81.25
219A-12-3-115-116	384.15-384.16	5.69	1164	1	10.6	84.58
219A-13-2-60-63	389.1-389.13	3.08	637	1.43		92.25
219A-14-3-32-33	405.32-405.33	3.8	1823	0.52	4	48.24
219A-14-3-138-140	406.38-406.4	3.62	615	1.03	9.2	91.14

*Not plotted in Fig. 5.

†Not plotted in Figs. 4 and 5.

TABLE 5 — MAXIMUM AND MINIMUM CONCENTRATIONS OF Fe, Mn, Ti, CaCO₃ AND ACID INSOLUBLES IN SEDIMENTS AND ROCKS FROM SITE 219

Unit	Depth (m)	Iron (%)		Manganese (ppm)		Titanium (%)		Calcium carbonate (%)		Acid insolubles (%)	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
I	0-120	1.06	2.59	146	331	0.11	0.32	42.8	71.4	20.29	48.2
II	120-145	0.09	0.43	22	192	0.029	0.09	83	88.6	5.4	9.75
III	145-219	0.12	0.52	152	230	0.025	0.065	55.6	85.6	8.5	35.8
IV	219-300	0.24	0.67	219	8476	0.015	0.092	64.8	93.4	7.05	34.55
V	300-411	0.59	8.06	442	1823	0.08	1.43	3	88.6	9.6	92.25

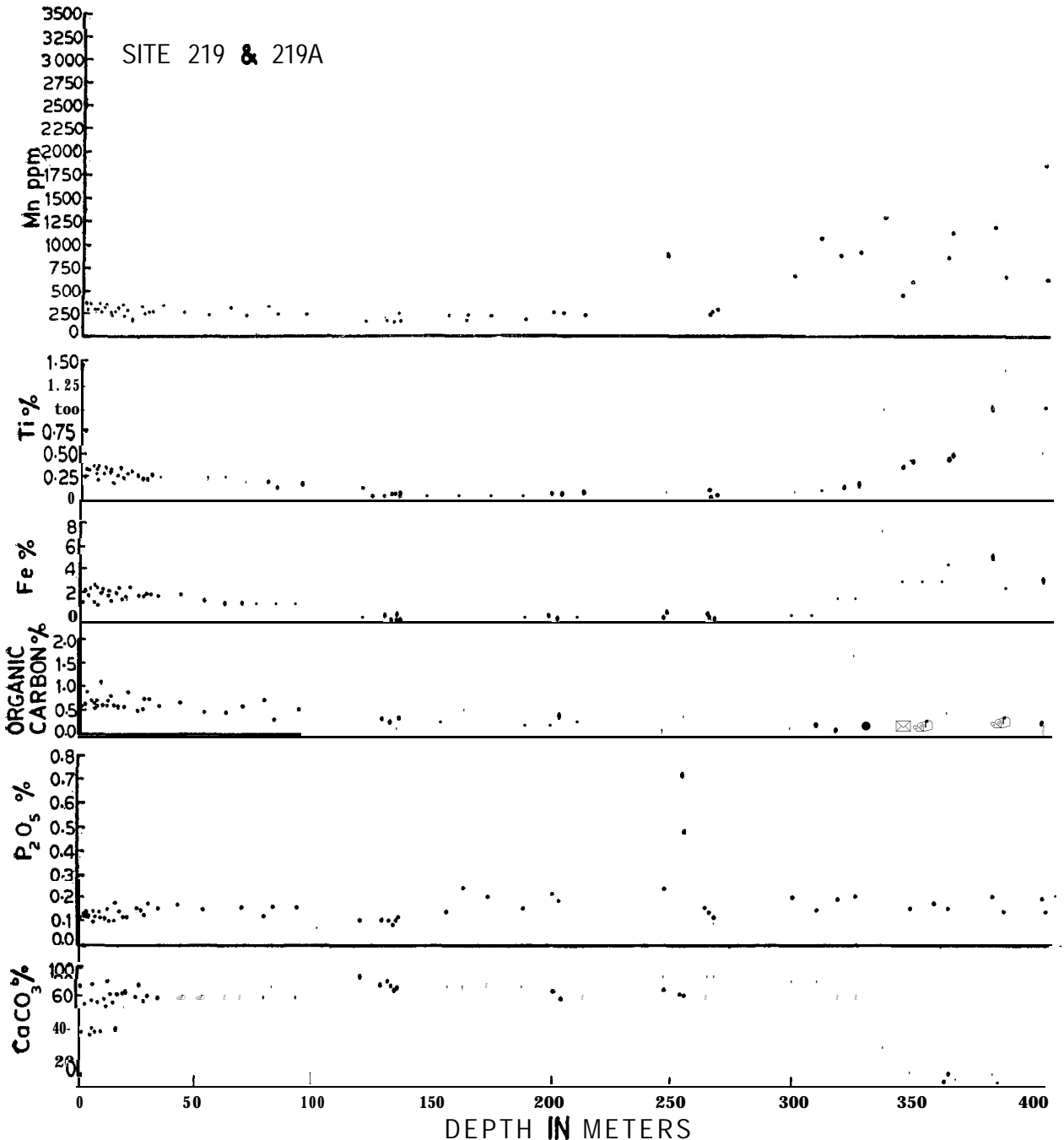


Fig. 4-Chemistry of sediments and rocks from Site 219 [Figure shows the depthwise distribution of CaCO₃, P₂O₅, organic carbon, Fe, Ti and Mn]

TABLE 6 — VARIATIONS OF Fe, Mn, Ti AND CaCO₃ IN DIFFERENT RANGES OF ACID INSOLUBLES IN DIFFERENT UNITS FROM SITE 219

Elements/ Constituent	Range of percentage of acid insolubles							
	0-10	10-20	20-30	30-40	40-50	50-60	80-90	90-100
UNIT I								
Fe (%)	—	—	1.06-1.53	1.09-2.08	2.07-2.59	—	—	—
Ti (%)	—	—	0.11-0.16	0.19-0.26	0.24-0.32	—	—	—
Mn (ppm)	—	—	196-331	191-326	146-309	—	—	—
CaCO ₃ (%)	—	—	61-71.4	54.4-61.7	42.8-55.2	—	—	—
UNIT II								
Fe (%)	0.09-0.43	—	—	—	—	—	—	—
Ti (%)	0.029-0.09	—	—	—	—	—	—	—
Mn (ppm)	22-191	—	—	—	—	—	—	—
CaCO ₃ (%)	83-88.6	—	—	—	—	—	—	—
UNIT III								
Fe (%)	0.17-0.2	0.12-0.24	0.29-0.35	0.52	—	—	—	—
Ti (%)	0.025-0.038	0.029-0.036	0.058-0.065	0.059	—	—	—	—
Mn (ppm)	152-208	157-185	219-230	207	—	—	—	—
CaCO ₃ (%)	81-85.6	76.8-83.6	66-71.2	55.6	—	—	—	—
UNIT IV								
Fe (%)	—	0.3-0.59	0.63-0.67	—	—	—	—	—
Ti (%)	—	0.015-0.069	0.082-0.092	—	—	—	—	—
Mn (ppm)	—	230-3463	219-8476	—	—	—	—	—
CaCO ₃ (%)	—	74.8-93.4	64.8-69.8	—	—	—	—	—
UNIT V								
Fe (%)	0.59	0.74	2.19-2.32	—	3.77-3.8	8.06	3.67-5.69	3.08-3.67
Ti (%)	0.081	0.13	0.14-0.13	—	0.39-0.52	0.99	0.43-1	0.49-1.43
Mn (ppm)	654	1043	860-896	—	442-1823	1274	581-1164	615-852
CaCO ₃ (%)	88.2	88.6	63.4-73	—	41-43.6	32	9.1-5	3.9-2

and titanium (Fig. 5), suggest that the detrital material is the major source for iron and titanium and that there is a close relation between iron and titanium in these sediments. A similar linear relationship between iron and titanium in deep sea sediments has been observed by El Wakeel and Riley¹⁷ and Revelle¹⁹. Iron and titanium contents of sediments at this site may be largely attributed to the iron and titanium bearing minerals occurring in different units, the volcanic glass and volcanic ash occurring in Unit I and to the montmorillonite clay (nontronite ?) occurring in sub-units Vb and Vc. Studies on the partition of iron among different components of sediments show that except in Unit V where glauconite occurs, the contribution of iron from the nonlithogenous fraction to the concentration of iron in the total sample is 0-10% indicating that most of the iron in these sediments is tied up with the detrital material. In view of the close correlation between iron and titanium this may be true in the case of titanium too.

With the exception of some high values in Unit IV the distribution pattern of manganese is similar to that of iron and titanium. Sediments and tuffs of Unit V have highest concentrations of manganese and lowest concentrations are in Units II and III. Sediments of Unit I have relatively higher concentrations of manganese than sediments of Units II and III. Despite this apparent similarity in

distribution, manganese does not show any covariance with iron and titanium but it exhibits different behaviour. It does not show any relationship with the percentages of acid insolubles or an inverse relationship with calcium carbonate. These indicate that though part of the manganese of the sediments may be tied up with the detrital material, a considerable portion of it may have been derived from some other source, i.e., non-lithogenous sources. Estimations of manganese in the acid soluble fractions of sediments and tuffs from Unit V show that 40-80% of manganese in total samples is contributed by the non-lithogenous fraction of sediments. In the absence of any discrete authigenic manganese minerals in these sediments, chemical precipitation of manganese in any significant measure can be ruled out. Sulphide minerals i.e., pyrite has been reported from some samples, though these could have accommodated some manganese in their structure it is doubtful if this mechanism can be invoked to explain the distribution of manganese in the entire Unit V. Similarly, the post-depositional migration of manganese cannot be ruled out entirely in view of the presence of some reducing zones. It cannot be regarded as a major process governing the distribution of manganese as the basal sediments of Unit V have a higher concentration of manganese than overlying sediments of Units IV to I. It is therefore suggested that

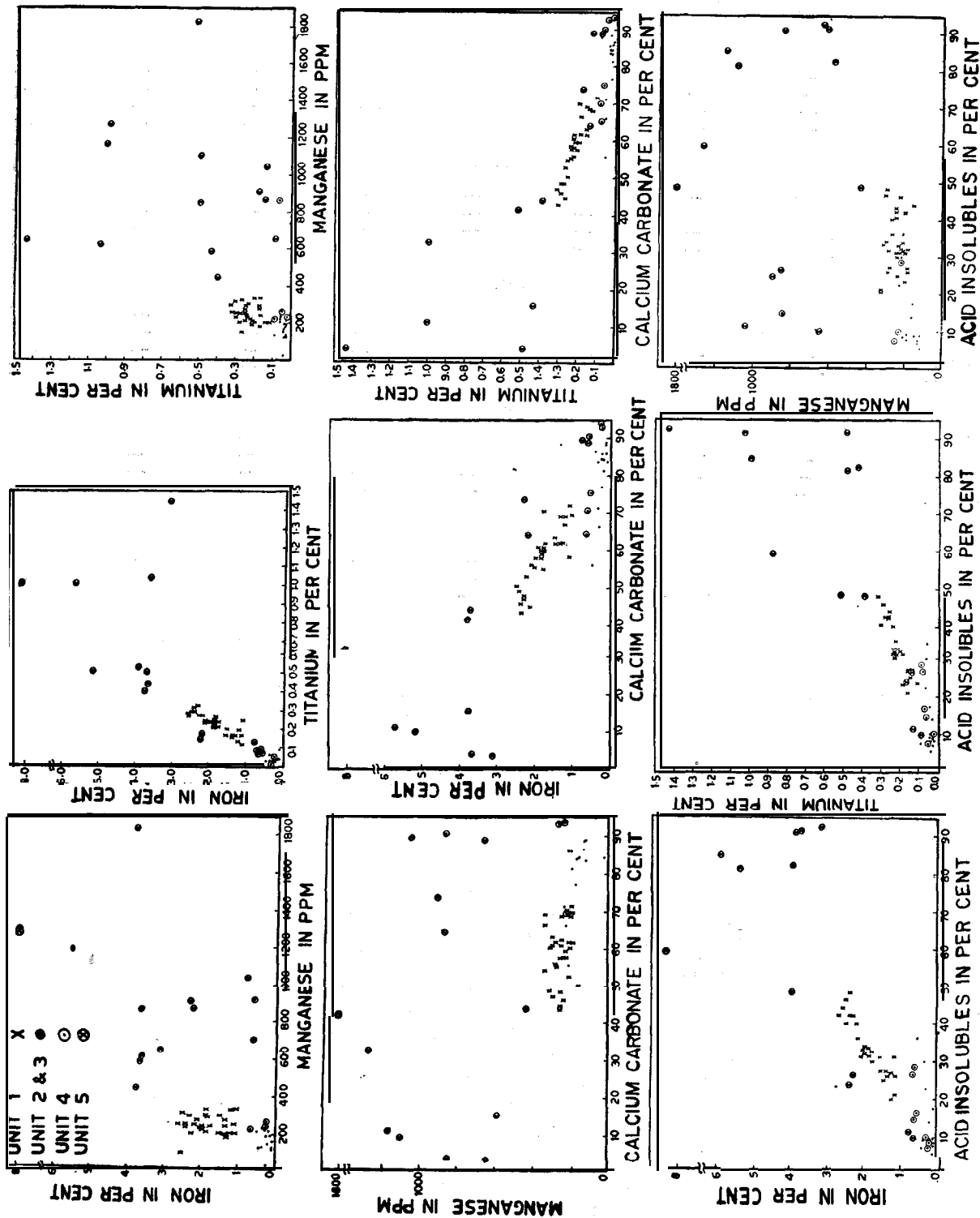


Fig. 5 — Scatter plots showing relationship between various elements and constituents

manganese may be largely associated with montmorillonite in Unit V. Manganese to the extent of 300 to 500 ppm has been reported from the montmorillonite and illite clays of the western continental shelf of India by Murty *et al.*²⁸. Excess manganese in these sediments may have been supplied by the volcanic activity in the area i.e., piroclastics and hydrothermal solutions. However, the manganese is not associated in significant amounts with clay minerals in other units and also in sub-unit Va and most of this may have been derived from other sources. Sediments of Units II to IV and sub-unit Va are largely biogenic while those of Unit I are partly terrigenous. In the absence of any inverse relation between the manganese and calcium carbonate contents it is very likely that part of the manganese in these sediments has been derived through the biological sources. The absence of any correlation between manganese and calcium carbonate may be because the calcium carbonate compensation depth rose as a result of upwelling during the post early Miocene period²⁹. Thus in the upper 4 units while part of the manganese may be associated with the detrital material it is tentatively suggested that a major part may be biogenic.

High contents of iron, manganese and titanium coupled with high content of montmorillonite, fresh unaltered feldspars and zeolites confirm the dominant volcanic nature of Unit V. Exceptionally high values of manganese recorded in Core 25 and 26 (Unit IV) may be due to upwelling during the Early Eocene. Similar high concentrations of manganese associated with upwelling have been reported by Maxwell *et al.*³⁰.

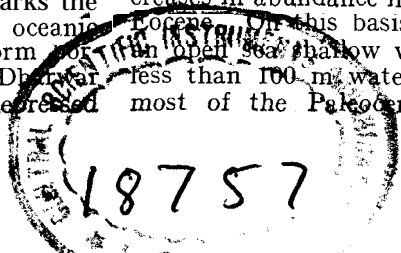
Site 219 and the Western Continental Margin of India

The available data on the geology of the Western Continental margin of India is meagre to draw conclusions on the tectonic history and sedimentation in the area, nevertheless some generalizations may be made.

The Indian Craton has long been considered to have extended further to the west but has been partially faulted down into the Arabian Sea. The interpretations and correlations of the Laccadive trend with the trends in the Indian peninsula varied considerably. Krishnan³¹ considered the Laccadive trend to be continuing into the Cambay basin and further to the Aravalli range and that faulting during the mid-Miocene or later times has down faulted parts of Deccan basalts beneath the sea. Harinarain *et al.*³² considered that the ridge may continue northwards up to Karachi. Pepper and Everhart³³ speculated that the Deccan Traps extended further west up to even the Carlsberg Ridge. Eremenko³⁴ and Eremenko and Datta³⁵ postulated that the Mesozoic outline of the Indian Platform bounded by the continent forming faults developed during the end of the Mesozoic era and it passes to the west of the Laccadives and this marks the transition between the continental and oceanic crusts. The western margin of the platform bordered by the ridge was formed during the Dharmar times. Sedimentation took place in the depressed

part of the platform between the ridge and the Western ghats in a basin extending from Cambay to the east of the Laccadive Islands. In Paleogene and Neogene times, the central part of this territory showed intensive subsidence along the fractures, leading to the development of an intracratonic graben shaped north plunging basin. Harbison and Bassinger's³⁶ studies of sub-bottom profiles indicated that linear fault block fragments create a basement ridge that extends to lat. 20°N and interpreted this to be the NW continuation of the main Laccadive structural trend and that this may be a relict margin of the Indian continent. Harbison and Bassinger³⁷ suggested that the sedimentary basin off Bombay is a triangular shaped asymmetrical basin resembling a half graben, with its maximum width off Bombay, this either dies out or is restricted along the narrow shelf south of 16° lat. Data of Eremenko and Datta³⁵ indicate that in the Laccadive-Cambay graben the maximum thickness of sediments have accumulated in the northern area. In the Laccadive-Kerala region the thickness of sediments is about 2-2.5 km in the central area (Elikalpeni) and it apparently decreases to the west (Kalpeni — 1.5 to 2 km) and to the east (Alleppey 2 km). The thickness of sediments in the northern area is considerably more, i.e. 3.5 km off Bombay and 5 km in the adjacent area to the west. Rao³⁸ reporting the results of seismic work of *RV Meteor* and *INS Kistna* indicated that the deepest layer of crust with P-wave velocity of about 6.2 km/sec was observed at depth of 5.5 to 6.4 km on the shelf and slope off Bombay. He estimated that the thickness of sediments over the shelf and slope to be of the order of about 2-2.5 km. The thickness of sediments may be more as the 4.33 km/sec layer considered by Rao³⁸ to be volcanic ash may represent at least in part sediments also. Further north in the Cambay basin the sediment thickness again decreases and about 2-3.5 km of Tertiaries lie the Pre-Cambrians and Deccan Traps³⁹. Towards the west and north west of Laccadive Ridge lie the dominantly terrigenous sediments of the Indus cone, the thickness of these sediments increases towards the mouth of the Indus. The ridge it appears separates the 2 distinctly different sedimentary facies in the Arabian Sea, the terrigenous sediments of the Indus Cone and the dominantly biogenous and chemogenous (carbonate) sediments to the east of the ridge.

Mangain *et al.*⁴⁰ studied the benthonic foraminifera in the Paleocene-Eocene section of site 219. They identified 66 genera but found the absence of benthic forams in barrels 10, 11 and 13 of 219A. The absence of benthic forams in these barrels was interpreted by the authors due to unfavourable ecological conditions. The present studies indicate that the unfavourable conditions were largely the volcanic activity or rapid deposition of volcanogenous sediments. The benthonic foraminifera increases in abundance in upper Paleocene and Lower Eocene on this basis Mangain *et al.*⁴⁰ suggested an open sea shallow water neritic environment of less than 100 m water depth for site 219 during most of the Paleocene and Eocene times. The



reported occurrence of *Discocyclus* *ramayao* Samanta⁴¹ is of considerable interest, the occurrence shows intermingling of fauna of east coast of India with the fauna from the present site. These may be interpreted as Krishnan³¹ did to indicate the interminglings of west and east coast fauna and opening of the gap between Ceylon and India. This observation seems to indicate that the present site was connected with the eastern shelf during late Paleocene and the western shelf extended as far as the Laccadive ridge. The decrease in benthonic foraminifera and the abrupt increase in planktonic forams in Early Eocene indicate that subsidence of the ridge began in Early Eocene and continued till about the Oligocene after which it decreased considerably. It was probably the period when the present configuration of the western continental margin of India started taking shape.

The faulting at the ridge and its subsidence were related to some of the major events taking place in peninsular India and particularly on the west coast (Table 7). The culmination of the Deccan Trap volcanic activity on peninsular India and eruption of rhyolitic tuffs at the Laccadive Ridge were followed by the formation of the Cambay graben and subsidence of the Laccadive ridge and all these appear to be connected events. The subsidence of the ridge was possibly related to the large anticlockwise rotation⁴² of the Indian peninsula in Cretaceous to Early Eocene which opened up the Cambay-Laccadive graben and led to the formation of the Laccadive Sea. It is expected that the Deccan Traps and the associated volcanics form the basement on which sedimentation took place in the Cambay-Laccadive graben. Sedimentation started with the deposition of the first

TABLE 7 — MAJOR EVENTS ON THE LACCADIVE RIDGE AND IN INDIA

	Laccadive Ridge (Site 219)	West coast	East coast	Hima'ayas
Pleistocene		Pleistocene : E.W. faulting in the Rann of Kutch ³¹	Uplift of Miocene strata ³¹ Late Pliocene-Early (Pleistocene)	Rise of Pir Panjal Range ³¹
Pliocene		Late Pliocene: Faulting on the west coast and raising of Mio-Pliocene strata. Uplift of South West Peninsula provid- ing eastward slope		4th uplift of Himalayas? (End of Pliocene)
Miocene	Minor unconformity ³	Marine transgressions'	Marine transgression**	3rd uplift of Himalayas ⁴⁵ (Mid Miocene)
Oligocene		Marine regression ³¹	Marine regression ³¹	
Late Eocene	Minor uncorformity ²			2nd uplift of Himalayas" (Up. Eocene)
Middle Eocene	Post Middle Eocene : Faulting (?) effecting chert reflector			
Early Eocene	Minor unconformity Fauna in overlying ² sedi- ments indicates depth of several 100 m. Subsidi- ence of ridge began here Shallow water (< 50 m) ² sediments, fauna indi- cates similarities with the Pondicherry forma- tion of East Coast	Faulting in Cambay Basin and formation of graben ³¹	Early Eocene regres- sion ³¹	
Upper Paleocene	Eruption of rhyolitic tuffs	Faulting at this time ex- tended northwards to Cambay ³¹ . Separation of India from Madagas- car ³¹	Eruption of Deccan Traps ⁴⁵	
Cretaceous	Faulting on the western margin of Laccadive Ridge ³⁴		Free mingling of fauna of Indo-Pacific and Mediterranean pro- vinces ³¹	1st of initial deforma- tion in Himalayas ⁴⁵

weathering products of the basalts or tuffs, i.e., sub-units Vb and Va on the Laccadive Ridge and the Trap wackes and Balutri formation of the Cambay basin. By about this period major water sheds of the Indian Peninsula had started taking shape and possibly the major rivers of the southern India had started flowing towards the east. In this event only limited quantities of terrigenous sediments would have been supplied to the Cambay-Laccadive graben and largely biogenous or chemogenous sedimentation would have taken place in the western area.

Eremenko³⁴ has suggested a late Cretaceous age for the N-S faults in the area which probably preceded the subsidence of the ridge in Lower Eocene, and the NNE fault scarps² may be of the same age. The other period of faulting discernible in the sub-bottom profiles made by DV Glomar Challenger is post-middle Eocene, this faulting appears to have disturbed the Eocene cherts. This faulting may be broadly correlated with the late Neogene-Quaternary age of faulting assigned to the west coast and the north east coast of Ceylon. It is also possible that some of the earlier faults could have been reactivated during this period. In the section shown by Eremenko³⁴ a zone of facies change is shown referring to terrigenous facies in the east and carbonate facies in the west in the Laccadive graben. Present data indicate that the facies change may not be valid for the Paleocene or Eocene. The Paleocene on site 219 on the Laccadive Ridge is largely volcanic and the Paleocene in the intervening tract between the West Coast and Kerala may also be expected to be similar. If the section (Eremenko)³⁴ and the stratigraphy of site 219 are compared certain similarities are discernible. These are significant thick Paleocene-Eocene and Miocene sequence and a thin Oligocene sequence.

The mineralogy and geomistry of the sediments and tuffs indicate that the sediments at site 219 can be broadly divided into 2 types. The dominantly volcanic rocks and sediments of Paleocene (sub-units Vb and Vc) and the biogenous sediments of Units IV, III, II and I. These 2 different types of sediments were deposited in different environments and this led to significant differences in their mineralogy and geochemistry. Volcanic pyroclastics chiefly tuffs and emanations provided a high concentration of montmorillonite, Fe, Mn and Ti in the sediments of Unit V. These conditions continued till volcanic activity subsided at the site. Even after this explosive volcanic activity, weathering and alteration of volcanic rocks continued in adjacent areas which is indicated by the occurrence of tuffaceous fragments and the slightly higher content of Fe, Mn and Ti in the overlying sediments of sub-unit Va and unit IV. The subsidence of the ridge during the Lower Eocene marked the end of this environment and the site passed to the deeper region of predominantly biogenous sedimentation. During this transition of the site from shallow to deep sea a significant change in the geochemistry of the sediments took place i.e., the deposition of phosphorite and enrichment of Mn in the sediments for a brief period in early

Eocene (Barrel 26). The entire Unit V and barrel 27 do not contain phosphorite, Unit V is dominantly volcanogenous and fauna indicates that sediments of barrel 27 were laid down in less than 50 m water. Fauna associated with sediments in barrel 26 indicated that the sediments were deposited in depth of more than 100 m i.e., off shelf but the immediately overlying sediments were deposited in fairly deep water i.e., middle and lower bathyal environment⁴³. Thus the entire Unit V and the lower part of Unit IV (barrels 27 and 28) were deposited in shallow water of less than 50 m depth. It is only when sinking began and the site was at shelf edge (Lower Eocene), terrigenous sediment supply was considerably reduced and conditions became favourable for precipitation of phosphorite and manganese from upwelled waters. However, these conditions existed only for a brief period and with continuing subsidence the site passed to the bathyal zone and by Middle to late Eocene the site was in abyssal area and biogenous sedimentation predominated. The conditions were no longer favourable for the formation of phosphate or manganese rich sediments. The depthwise distribution of P_2O_5 given in Fig. 4 and the presence of micronodules of phosphorus in the sediments of this restricted zone supports this surmise.

McKelvey⁴³ is of the view that in areas of present upwelling, the upwelling may date back to late Mesozoic when the present configuration of the continents had taken shape. The western shelf of India is a prominent area of upwelling and the occurrence of phosphorite in Lower Eocene indicates that upwelling in this area dates back to at least the Lower Eocene. Even if any upwelling occurred in the area earlier during the Paleocene, there is little likelihood of formation of phosphorite as chemical precipitation would be diluted by the large amount of terrigenous material. The inference that the present upwelling on the western shelf dates back to the Eocene indicates that the area has been a rich organically productive one since early Tertiary. This may have been important in producing large quantities of organic matter for source beds that may lead to the accumulation of oil, gas and sulphur. It is however, noticed that the organic carbon in general is less than 1% throughout the sedimentary column (Fig. 4). It appears that eventhough the area has been rich (organically productive) conditions for the preservation of organic matter have been favourable for brief periods only.

Acknowledgement

The authors are grateful to Dr R. B. Whitmarsh, Institute of Oceanographic Sciences, UK, and Dr O. E. Weser, Deep Sea Drilling Project, Scripps Institution of Oceanography, USA for critically going through the manuscript and suggesting modifications and to Dr S. Z. Qasim, Director, for his constant encouragement and for going through the manuscripts. The authors thank their colleagues Dr V. Narayanan and Shri G. V. Rajamanickam for their help during the laboratory studies.

References

1. WHITMARSH, R. B., WESER, O. E. & ROSS, D. A. et al., *Geotimes*, 17 (1972), 22.
2. WHITMARSH, R. B., WESER, O. E. & ROSS, D. A. et al., *Initial reports of the deep sea drilling project 23* (US Government Printing Office, Washington), 1974, 1180.
3. GOSWAMI, J. N., personal communication.
4. SIDDIQUIE, H. N. & SUKHESWALA, R. N., *J. geol. Soc. India*, (1976), (in press).
5. RAJU, A. T. R., *Bull. Am. Assoc. petrol. Geologists*, 52 (1968), 2422.
6. ROYCHOWDHURY, S. C., MATHUR, R. B. & MISRA, C. S., *Bull. Oil Nat. Gas Comm. India*, 9 (1972), 57.
7. MATTI, J. C., ZEMMELS, I. & COOK, H. E., in Whitmarsh, R. B., Weser, O. E., Ross, D. A. et al., *Initial reports of the deep sea drilling project, 23* (US Government Printing Office, Washington), 1974, 1137.
8. GOLDBERG, E. D. & GRIFFIN, J. J., *Deep Sea Res.*, 17 (1970), 513.
9. HUNZIKER, J. & MATTER, A., in Whitmarsh, R. B., Weser, O. E., Ross, D. A. et al., *Initial reports of the deep sea drilling project, 23* (US Government Printing Office, Washington), 1974, 45.
10. PORRENGA, D. H., *Fysisch Geografisch Lab. Univ. Amsterdam Publ.*, 9 (1967), 145.
11. CHESTER, R. & HUGHES, M. J., *Trans Instn Min. Metals (Appl. Earth Sci.)*, 77 (1968), 37.
12. SANDELL, E. B., *Colorimetric determination of traces of metals* (Interscience, New York), 1959, 1032.
13. RILEY, J. P., *Anal. Chim. Acta*, 19 (1958), 413.
14. MÜLLER, G., *Methods in sedimentary petrology* (Schweizerbart Verlag, Stuttgart), 1967, 283.
15. CHESTER, R. & HUGHES, M. J., *Chem. Geol.*, 2 (1967), 249.
16. GOLDBERG, E. D. & ARRHENIUS, G., *Geochim. Cosmochim. Acta*, 13 (1958), 153.
17. EL WAKEEL, S. K. & RILEY, J. P., *Geochim. Cosmochim. Acta*, 25 (1961), 110.
18. GOLDBERG, E. D., *J. Geol.*, 62 (1954), 249.
19. REVELLE, R. R., *Carnegie Inst. Wash. Publ.* 556, 1944, 1.
20. CARROLL, D., *Geochim. Cosmochim. Acta*, 14 (1958), 1.
21. CORRENS, C. W., *Deep Sea Res.*, 1 (1954), 78.
22. PETERSON, H., *Medd. Oceanog. Inst. Goteberg*, 2B (1945), 1.
23. LYNN, D. C. & BONATTI, E., *Marine Geol.*, 3 (1965), 457.
24. BONATTI, E. & NAYUDU, Y. R., *Am. J. Sci.*, 263 (1965), 17.
25. GRAHAM, J., *Science*, 129 (1959), 1428.
26. LI, Y. H., BISCHOFF, J. & MATHIEU, G., *Earth Planet. Sci. Letters*, 7 (1969), 265.
27. PRICE, N. B. & CALVERT, S. E., *Marine Geol.*, 9 (1970), 1045.
28. MURTY, P. S. N., RAO, CH. M. & REDDY, C. V. G., *Curr. Sci.*, 39 (1970), 30.
29. LA FOND, E. C., in *Encyclopaedia of oceanography*, edited by R. W. Fairbridge (Reinhold Publ. Corp., New York), 1966, 1031.
30. MAXWELL, A. E. et al., *Initial reports of the deep sea drilling project, 3* (US Government Printing Office, Washington), 1970, 806.
31. KRISHNAN, M. S., *Bull. nat. Inst. Sci. India*, 38 (1968), 398.
32. HARI NARAIN, K. L. & VERMA, R. K., *Canadian J. Earth Sci.*, 5 (1968), 1051.
33. PEPPER, J. F. & EVERHART, G. M., *U.S. Geol. Survey Prof. Paper*, No. 1380, 1963, 1.
34. EREMENKO, N. A., *Geol. Soc. India Mm.* (1968), 371.
35. EREMENKO, N. A. & DATTA, A. K., *Bull. Oil Nat. Gas Comm., India*, 5 (1968), 29.
36. HARBISON, R. N. & BASSINGER, B. G., *J. geophys. Res.*, 78 (1973), 432.
37. HARBISON, R. N. & BASSINGER, B. G., *Geophysics*, 35 (1970), 603.
38. RAO, T. C. S., *Symposium on Upper Mantle Project, Hyderabad, India*, 1967, 342.
39. KALININ, N. A., *Proceedings of 22nd International Geology Congress, New Delhi, Part I, Sec. I, 1964*, 244.
40. MANGAIN, V. D., CHATTERJEE, B. P., SEN, M. K. & MISRA, R. S., in Whitmarsh, R. B., Weser, O. E. & Ross, D. A. et al., *Initial reports of the deep sea drilling project, 23* (US Government Printing Office, Washington), 1974, 44.
41. SAMANTA, B. K., *Micropaleontology*, 13 (1967), 233.
42. ATHAVALE, R. N., VERMA, R. K., BHALLA, M. S. & PULLIAH, C., in *Palaeogeophysics*, edited by S. K. Run-corn (Academic Press, New York), 1970, 219.
43. FLEISHER, R. L., personal communication.
44. MCKELVEY, V. E. & CHASE, L., *Second Ann. Trans. Marine Technology Society Conference*, 1966, 44.
45. KRISHNAN, M. S., *Geology of India and Burma* [Higginbothams (P) Ltd, Madras], 1968, 536.