# GEOCHEMISTRY OF THE HOOGHLY ESTUARY

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Dedicated to

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&

BITHIKA DIDI

## CERTIFICATE

This dissertation, entitled "Geochemistry of the Hooghly Estuary" embodies the work carried out at the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work has not been submitted in part or in full for any degree or diploma of any university.

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Any error is mine.

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# CHAPTER - I

## INTRODUCTION

The term 'estûary' comes from the Latin substantive "aestus", meaning heat, boiling, tide and especially the adjective "aestuarium", meaning tidal. There has been much of disagreement among the authors for the definition of the estuary. The definition given by Pritchard (1967) was discarded because it completely ignored the tidal and river qualification. The most acceptable definition was given by Fairbridge (1980) - (following Dionne, 1963) as "An estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, usually being divisible into three sectors : (a) a marine or lower estuary, in free connection with the open sea; (b) a middle estuary, subject to strong salt and fresh water mixing; and (c) an upper or fluvial estuary characterized by freshwater but subject to daily tidal action". The limits between these sectors are variable and subject to constant changes in the river discharge. Closely related to estuaries hydrologically, but different in terms of physical geography, are sounds, lagoons and deltas,

each of which may include or pass into an estuary (sensu stricto).

## CLASSIFICATION OF ESTUARY

The classification of estuaries has not hitherto been organized in any systematic way. Fairbridge (1980) made a preliminary approach to organize physiographic categories of estuary in terms of (a) relative relief and (b) degree of blocking; as mentioned below:

1. High relief estuary: U-shaped valley profile fjord; related, but more subdued relief.... fjord, firth, sea-lock.

2. Moderate relief estuary: V-shaped profile, winding valley... via; aber (western Britain); special limestone Karst type.... calanque, cola.

3. Low relief estuary: Branching valleys, funnel shaped plan... coastal plain estuary (open); flask shaped, partly blocked by bar or barrier island (with lagoons or sounds).... coast plain estuary (with barrier).

4. Low relief estuary: L-shaped plan, lower course parallel to coast.... bar-built estuary.

5. Low relief estuary: Seasonally blocked by longshore drift and/or dunes, with or without eolianite bar... blind estuary.

6. Delta front estuary: ephemeral distributary... deltaic estuary; in interlobate embayment... inter-deltaic estuary.

7. Compound estuary: flask-shaped via backed by low plain... tectonic estuary.

In hydrodynamic terms, categories 1-2 are so-called "disequilibrium estuaries", while 3-7 are mainly "equilibrium" or "constructional" estuaries, as pointed out by Fairbridge (1980).

However, this classification is a subject of regional variations because "dynamic environmental factors" (Fluvial hydrology; wave energy; tidal range; biologic sedimentary controls; sedimentology and mineralogy; Geotectonics and Neotectonics) can modify the nature of the estuary.

No attempt has been made to classify the Indian estuaries. So, there is a dearth of literature. Here, an attempt is being made to classify the Hooghly estuary - the largest one in India. The coastal plains of Orissa and Bengal pass under the Bay of Bengal with very little change of their gentle slope until 50 m. bathymetric contour is reached. The 10 m. bathymetric contour at the mouth of the Ganga appears to be very much jagged because of the strong tidal currents

sweeping the bottom sediments. The Bengal basin is so flat that a mere 4 m. rise of the sea-level would submerge Calcutta and its environs. The Ganga Delta occupies the major portion of the Bengal basin. Like any other great delta of the world, it has a web of distributaries near its seaward face, and shallow depressions near Calcutta contain salt water and are tidal. The delta has its seaward face influenced more by the tidal estuaries and less by the waves with the result that a maze of sand banks, mud flats, mangrove swamps, inlands and forelands characterise the indented coast-line. The Hooghly estuary below Diamond Harbour fans out from a width of 3.2 Km at Kantaberia to 19.3 Km at the sea-face in a distance of about 65 Km. So the Hooghly has a funnel shape and it has changed its course also in the past.

Thus, we see that the Hooghly estuary cannot be put in any single category of Fairbridge's classification due to its complex nature. It can be said to be a low relief interdeltaic estuary.

The bulk of the world's estuaries have only been in existence for the last 6,000 yrs, since when they have been progressively infilled aided by a eustatically oscillating sea level, and various

processes - characteristic of estuary. Therefore, it becomes relevant to review in brief, the estuarine processes. This will make the present work more understandable.

## ESTUARINE PROCESSES

The estuarine regions where freshwater-seawater reactions take place, are very important, since these regions modify the net outflow of material (both soluble and suspended) into the Ocean (Turekian 1977). The important processes are as follows:

### I. PHYSICAL PROCESS

Physical processes control the distributions and behaviour of many biologically reactive substances in estuary. Although there are difficult problems, which require increased understanding of the factors controlling currents and salinity distributions (c.f. Dyer 1976), some of the important physical processes are dealt with below.

#### I.a. Net Circulation Effects

In estuaries the tidal and gravitational circulation flows are dominant over the simpler riverine flow; the sedimentary particles are largely of clay and silt rather than sand size and suspended

material transport is the dominant mode observed rather than bed-load transport (Officer 1981).

Collins (1976) studied net circulation patterns and routes of suspended material transport in lower Narragnsett Bay and its approaches, utilizing sea-bed drifters, transmissometer measurements, grain-size distributions, suspended material concentration data and compositional analyses. He observed that in general sea-ward flowing near-surface currents carry silt and the landward flowing direction of bottom currents is modified by coastal currents and topographic influences. Based on his own and other workers' investigations, he maintained that Coriolis acceleration may cause the dextral movement of near-surface and near-bottom suspensates from the mouths of estuaries.

Peterson et al. (1975a) observed in the San Francisco Bay estuary that the seasonal variations in water chemistry and phytoplankton abundance are closely related to the general water circulation pattern.

Unlike riverine conditions in estuaries, the controlling factors are a combination of the longitudinal pressure gradient force slope or barotropic force, and that due to the surface

longitudinal density (salinity) gradient or baroclinic force. The barotropic force is constant as a function of depth and acts in a down-estuary direction whereas, the baroclinic force increases essentially linearly with depth and acts in an up-estuary direction. The combined effect of these two forces is to produce a net circulation down estuary in the upper portion of the water column and up-estuary in the lower portion of the water column. The theoretical description of this characteristic estuarine-type circulation has been given by Rattray and Hansen (1962) and Hansen and Rattray (1965) and in a more simplified form by Officer (1976).

Thus, as described by Postma (1967) and Schubel (1968, 1969, 1971) suspended particles traversing seaward in the upper portion of the water column at the middle to lower reaches of an estuary (where the gravitational circulation is well developed) sink and are carried back landward in the lower portion of the water column to produce a suspended sediment turbidity maximum in the upper to middle reaches of the estuary. This action forms an effective sorting mechanism; the coarser, silt-size particles would be expected to be deposited in the middle to lower

reaches of the estuary and the finer, clay-size particles to be carried back to form the turbidity maximum.

Further, the circulation near the bottom will be landward in the middle to lower reaches of an estuary, following the gravitational circulation flow and will be seaward in the upper reaches of an estuary - where there is no longitudinal salinity gradient and only riverine type flow exists. If near bottom, or bottom boundary-layer transport is important, there should be a significant depositional region in the null or convergence zone between these two opposing flows.

not clear

I.b. Turbidity

Festa and Hansen (1978) modelled the suspended-sediment turbidity maximum related to gravitational circulation effects. This was a conservative model with respect to the estuary itself and the predicted turbidity maximum was associated with the up-estuary region, where the river sediment source was dominant or comparable with the ocean source. The suspended sediment maximum was associated with salinity values around $\frac{\sigma}{10}$, where $\sigma$ is the salinity of the reservoir (ocean or bay) into which the estuary empties.

Officer (1980a) made a comparison of the numerical-model results of Festa and Hansen (1976) using an approximate two dimensional box-model, or finite-segment approach described by Officer (1980b). The box-model values predicted the same approximate location for the turbidity maximum and the box-model values were the same, particularly for small settling velocities. The advantages of the box-model approach are that within its inherent limitations, it can be easily applied to actual estuarine conditions and that it can be extended to the nonconservative case of the sediment flux exchanges with the bottom to determine first-order values for the wet erosion of deposition along the estuary.

I.c. Tidal Effects

Of particular importance is the phenomena of local tidal resuspension, i.e., the alternate suspension of particles from the bottom during periods of maximum flood and ebb currents and settling during the intervening slack periods. However, Allen et al. (1976) have shown that there can be substantial variations associated with the neap to spring tidal cycle.

The zone of transition between the wave dominated open coast and tide-dominated mouth of estuaries

is complicated. A time series study of wave parameters, longshore currents and tidal parameters at the mouth of an estuary on the northeast coast of Florida has demonstrated that tidal influence on nearshore process is modest and localized (Davis Jr. and Fox 1981).

Schubel et al. (1978) have made one of the few analyses of the vertical distribution and flux of suspended sediments as a function of the semi-diurnal tidal cycle. They have made a distinction between those particles in more or less continual suspension throughout the water column and those alternately suspended and deposited. The background consists of particles with Stoke's diameters upto about 2 um and those alternatly suspended and deposited, diameter of 2-64 um. They calculated the vertical fluxes as a function of tidal time at various heights above the bottom and related the calculations to the particle settling flux and the vertical diffusion flux.

Simple dynamical considerations indicate that there will be some lag between the tidal curve affecting the magnitude of suspended material near the bottom, and the suspended distribution throughout

the water column. For an asymmetric tidal cycle in which the duration between ebb and flood current maxima is less than that between flood and ebb maxima, there will be a larger duration following the flood maximum and a consequent net transport in the flood direction. The duration of the ebb and flood phases may be different in shallow, tidal areas with a consequent variation in flood and ebb current amplitudes; the amounts resuspended during the flood and ebb will differ and a net transport can result. Postma (1961) observed that the additional landward transport was related to the asymmetric tidal cycle in the inlet channels with a shorter duration between maximum ebb and flood than between maximum flood and ebb and a consequent transport landward. Boon (1974, 1975) added to the importance of this type of transport in his investigations in a salt marsh drainage system in Virginia. Here, the tidal asymmetry curves were reversed from those in the Wadden sea with the duration between maximum ebb and flood being longer than that between maximum flood and ebb; and the transport was seaward. Groen (1967) has given a theoretical description of the non-linear transport related to lag effects, but his basic equation describing the processes is a postulated relation.

Boon (1978) has discussed the difficulties in assessing net sediment transport in salt-marsh systems in which the net transport is small as compared with the flood or ebb half-cycle transport.

It would seem that substantial gain could be made in our understanding of suspended sediments by studying more fully both the vertical and longitudinal distribution and transport effects throughout a tidal cycle and the bottom source conditions and determining factors related thereto. Such studies require both the appropriate theoretical and observational determinations.

I.d. Plumes and Fronts Effect

Plumes of low salinity water spreading horizontally over the underlying sea water are of common occurrence where a stratified estuary enters a wider channel or the open sea and are particularly pronounced when they occur in association with a salt wedge estuary. Plumes are characteristically very shallow. As the river water spreads, sea water is entrained from below so that there is an increase in the salinity and volume of water in the plume. A dynamical treatment leading to a method of predicting changes in the breadth, thickness and

other properties of a spreading plume was given by Wright and Coleman (1971) and they related it to observed conditions at the mouth of the Mississippi.

Fronts tend to develop at the lateral boundaries of a plume. A study of the plume formed by the Connecticut River flowing into Long Island Sound and the associated fronts was made by Garvine (1974) and Garvine and Monk (1974). A front is characterized by the isohalines rising steeply to the surface, with a sharp horizontal gradient in salinity. The front itself tends to advance over the lower layer velocity than that of water in the surface layer. The front is, in fact, a zone of convergence with surface water sinking along the interface between layers. In addition to having a sharp transition in salinity, a front is often marked by a change in colour and turbidity of the water and a line of foam or debris, concentrated by the convergence.

I.e. Temperature

Smith (1978) noted that both the temperature and salinity variation give rise to buoyancy-driven currents. Thus, when hot water is discharged into estuaries the flow is changed both by heat and by induced perturbation of the salinity distribution.

He concluded that the interactions between heat and salt lead to the heat being preferentially dispersed inland.

I.f. Weather and Storm

Weather patterns may have an important effect on tidal processes at the estuary mouth because they control wave impingement and therefore, long-shore current speed and direction. Longshore currents may reinforce or suppress tidal currents, particularly in lateral channels.

Nichols (1977) reported that Tropical Agnes produced a four-fold stress on the Reppahannock Estuary; first a storm tide, then river flooding, and high sediment influx, followed by freshwater inflow through the mouth. As flood energy dissipated through the upper estuary it broke down the normal partly mixed regime and changed the near-bed transport direction from landward to seaward. Flooding of the lower estuary changed the partly mixed regime to a salt-wedge and triggered a sequence of hydraulic events. The flood energy mainly produced a large transport of suspended sediment within the estuary. He noticed that the sediment that escaped further, seaward in the low salinity surface layer during late

flood stages was entrapped by the closed estuarine circulation which was strengthened and retained in the estuary during all stages of flooding of the total sediment influx, about 90% was trapped within the estuary and deposited mainly in the zone of the turbidity maximum.

## II. CHEMICAL PROCESSES

Estuaries are regions of fundamental importance with respect to geochemical processes occuring on the global scale, for they represent the major route whereby weathered lithospheric material is transported to the oceanic sedimentary domain. Many global geochemical mass-balance calculations assume chemical continuity between rivers and ocean water, neglecting the probability of rapid chemical interactions in the estuarine region brought about by the sharp change in physico-chemical conditions of the aqueous environment across the interface (Morris 1978).

Controlled laboratory experiments have been used in attempts to elucidate chemical interactions in estuarine systems (Sholkovitz 1976). Although providing an insight into the types and extent of reactions that may occur, realistic laboratory simulations of the complex and rapidly varying conditions

obtained in the field are quite impractical, and are therefore, limited in their predictive output.

II.a. Physico-Chemical Condition

Numerous direct attempts to obtain field description of interactive processes in estuaries have been made. In reviewing the available literature, Boyle et al. (1974) concluded that there appears to be no generality in the reported interpretations either of the extent of non-conservative behaviour or of the mechanisms involved. Morris et al. (1982) pointed out that the difficulties in drawing generalized conclusions concerning estuarine chemistry from the available literature arise from the continuous variability, both long and short-term of estuarine physical and physico-chemical properties and the unique combination of the properties exhibited by any estuary at any one time. Even so, the majority of field studies have failed to consider the physical and physico-chemical condition prevalent at the time of investigations. If field investigations of estuarine chemical interactions are to be fully interpretable and intercomparable, simultaneous physical and physico-chemical data must be obtained and reported.

Many of the cyclic or intermittant phenomena that potentially influence chemical reactivity within the estuarine system are manifested over time intervals appreciably shorter than required for replacement of water (Morris 1978). For example, the rate of input and composition of freshwater run-off; tidal velocities and related particle suspension and deposition rates and diurnal biological activity all vary appreciably over periods of hours or less. It is probable, therefore, that if significant chemical reactions are occurring within an estuary, their rates and the instantaneous concentration of reactants and products will also vary over correspondingly short-time intervals.

At high flows, variations in suspended solids concentrations independent of those resulting from changes in discharge and erosion are difficult to establish. However, in semi-arid regions high concentrations of clay and silt may sometimes be transported. The way such concentrations reflect changes in water chemistry is illustrated by a fresh flood from Qued Kala Iris river, Morrocco and by the data from the Morean River, Bixby, South Dakota (Imeson and Verstraten 1981). However, in most studies of

suspended solids transport, river water chemistry is not considered as a factor influencing concentration levels. This is often justifiable but in certain cases, it is clear from the data and background information presented, that suspended solids concentrations might have been more adequately explained if water quality information had been collected and better rating curves established. Even when suspended solids transport is dominated by mechanical factors and concentrations are unrelated to the chemistry of the transporting medium in the river, the changing chemical environment of a river is still often important for the insight it provides into actual and potential soil erosion hazards, such as piping and gullying, which result from dispersion phenomena (Heade 1971; Imeson 1978).

The macroclinic conditions influence water and salt balances, and/or because topographic and vegetation conditions influence soil erosion and the relative importance of mechanical factors in producing high suspended solids concentrations. All the examples have in common a suspended load in which the proportion of clay and silt is high. In the absence of clay and fine silt particles, chemical effects are ofcourse, unimportant.

## II.b. Role of Electrolyte

Imeson and Verstraten (1981) have described the relationship between electrolyte concentration exchangeable sodium percentage and suspended solids concentrations in the drainage basin. Such relationship provides an insight into the nature of erosion processes in a catchment and helps to explain why suspended solids concentrations at low flows may be so variable. The changes in the electrolyte concentrations during hydraulic events result in an alternation between conditions favouring dispersion and those favouring flocculation.

The criteria necessary for unambiguous deduction of nonconservative behaviour are not well established. Essentially the concentration of an individual constituent throughout the estuarine mixing regime is used to deduce the relative proportions of the fresh and salt-water contributions to the mixed estuarine water (Morris 1978). Deviations from linearity of the constituent-salinity relationship indicate nonconservative behaviour only if the composition of the oceanic and riverine components have remained constant over the time period required to replace the water within the estuary, and if

curvature of the constituent-salinity relationship can be established, significant subsidiary freshwater inputs are complicating factors.

II.c. Adsorption-Desorption Process

The overall effect of adsorption-desorption processes occurring in estuaries is poorly known. However, many elements are conservative during estuarine mixing (e.g., U, B, ....) (Martin and Maybeck 1978; Fanning and Maynard 1978) while little field evidence for desorption has been given except for Ba (Edmond 1978) and some radioactive elements (Evans and Cutshell 1973). Finally, whenever precipitation onto particulates occurs, it usually affects chemical elements which have a low DTI (Differential Thermal Index) value, such as Fe and lanthenides, so that the concentrations of river particulates are not greatly altered (Martin et al. 1976; Figueres et al. 1978).

II.d. Alkalinity-Acidity (pH)

The acidity or alkalinity of an environment is an important factor in determining whether or not certain minerals will precipitate. At pH 7.8 or even at higher pH, calcite freely precipitates out (Krumbein and Garrels, 1952). Silica tends to dissolve in the

Alkaline environment and precipitates in the acid environment. The relation between the solubility of silica, calcium carbonate and pH have been reviewed by Correns (1950).

Morris (1978) pointed out that the dominant factor in determining the pH distribution within the estuarine system at any time is the pH of the freshwater source. The short-term control of pH in natural aqueous system is dominated by the carbonate system. Mook and Koene (1975) have predicted that as a result of the influence of salt content, particularly on the activities of bicarbonate and carbonate ions, pH in the mixing region of estuaries will not show a regular transition between the fresh and sea water values. Rather, for freshwater sources of relatively low pH, there would be a minimum in the pH distribution at low salinity, whereas for freshwater sources of higher pH, a sharp decrease in pH would occur at low salinities. The overall pH-salinity relationship is also dependent on the total alkalinity of the fresh and sea water, temperature and the pH of the seawater.

## III. BIOLOGICAL PROCESS

Organisms, especially phytoplanktons play an important role in the recycling of some elements and nutrients. Peterson et al. (1975a, 1978) concluded that silica concentrations are also governed by the biological removal in the estuary. Photochemical reactions remove the hydrocarbons from the sea-surface. Besides this, human activities such as dredging, jettying and landfill etc. in an urbanized estuary, influence the sedimentological processes and water quality of the acquatic system. Since the present work does not deal with biological role played in the Hooghly estuary, so its description is not being given in detail.

## IV. GEOLOGICAL PROCESSES

Geologically estuaries are ephemeral. Like the rivers their main functions are transportation, deposition and erosion. In the estuaries, these processes are influenced by physical, chemical and biological activities. The structure and shape and size of the basin also play an important role in accelerating or decelerating the geological functions of the estuary.

With regard to transport and deposition or erosion, Simmons (1966) and Simmons and Brown (1969) discussed the null zone depositional effects in a number of estuaries. For the Thames, Inglis and Allen (1957) delineated two depositional zones, one associated with the null zone and the other seaward of the turbidity maximum; Nichols (1972) and Nichols and Poor (1967) delineated two similar depositional regions from historical bathymetric data for the James and Rappahannock estuaries, respectively. For the Gironde estuary, which is nearly filled and has a large sediment input, Allen et al. (1974) estimated that there is a net discharge of sediment to the coastal region of half the river derived suspended sediment input. For Chespecke Bay Schubel and Carter (1976) have determined that there is a net transport of sediment into the bay from the Ocean and also a net transport from the Bay to its estuaries. For two of these tributary estuaries, James and Rappahannock, Officer and Nichols (1980) have used the box model approximation for gravitational circulation effects to determine that under moderate river flow conditions, there is a comparable flux of suspended sediments into the estuaries from both the river and

the bay and that the principal depositional zone related to these fluxes is seaward of the turbidity maximum. They speculated that the near bottom and nonlinear tidal transport effects, not included in their analysis, produce an additional depositional region in the vicinity of the null zone in these two estuaries. Odd and Owen (1972) and Krone and Ariathurai (1976) have modelled some aspects of the near bottom transport and depositional effects for the Tames and Savannah estuaries, respectively. Sedimentological studies in estuaries and near-shore marine environments have traditionally utilized grain-size, mineralogical and suspended solid measurements (Allen et al., 1972; Veerayya and Varadachari 1975; Mallik 1976, 1978; Gibbs, 1977; Officer 1980; Ward 1981).

Thus, all these processes operating within an estuary give a clue that environmentally meaningful results can be obtained only by in-situ investigations using an experimental procedure designed to characterize simultaneously those prevailing environmental conditions, and their geographical and temporal variability, that influence chemical specification and reactivity.

## PREVIOUS WORK

While discussing the various estuarine processes, a good deal of discussion has already been given. However, in the succeeding pages, a brief account of work done on the important world estuary and Indian rivers are being given.

### Amazon Estuary (S. America)

This is a much talked about estuary draining an area of 613 X $10^6$ $Km^2$ (Keller, 1962) in the northern part of South America. The Amazon's annual average discharge of 175000 $m^3$/sec is 4.6 times that of the Congo and 11 times that of Mississippi river (Ottman, 1966). With respect to both drainage area and volume of discharge, the Amazon is the world's largest river. Its annual average discharge of sediments is 0.5 X $10^9$ tons (Postma, 1980).

In the Amazon the volume of river flow is so great that no appreciable amount of sea water penetrates the estuary at all, although the tidal influence extends upstream to a distance of 735 Km from the mouth. The mixing of sea water and river water takes place in the ocean, in a plume spreading as far as 1000 Km seaward from the river mouth (Gibbs, 1970).

Large quantities of mud are deposited in a long coastal zone stretching from the mouth of the Amazon river upto Orinoco delta (Postma 1980). The mud banks move slowly from east to west with a speed of about 1.5 Km per year, moving about $0.5 \times 10^9$ tons of sediment.

The surface water flow from the Amazon is sometimes drinkable upto 100 Km offshore (Olson 1970).

Avon River Estuary (Nova Scotia, Canada)

There are six major intertidal sand bodies in the estuary; three are at the estuary mouth (sea ward end) and the other three are near the estuary head (shore-water end). In addition there is a narrow sand ridge near the centre of the estuary that is subaerially exposed only at lower low water. The sand bodies form parts of ebb and flood tidal deltas (Lambaise, 1977) and have morphologies that are similar to the mesotidal tidal delta models of Hayes (1975).

Lambaise (1980) concluded that in the macro-tidal Avon River estuary, grain-size distributions is controlled by local current speed. This control is not reflected by textural parameters, but it is exposed by cumulative frequency curve analyses.

He emphasized that sorting is produced by the geometry of the sediment transport paths in the estuary with differential transport rates for each grain population. Fast moving intermittently suspended grains can by-pass an ebb channel that "traps" slow moving grains transported by traction. This excludes coarse sediment from the estuary head creating an inverse relationship between mean grain size and current speed.

Bristol Channel-Severn Estuary System (U.K.)

Bloxham et al. (1972), Butterworth et al. (1972), Chester and Stoner (1975) and Hamilton et al. (1979) have studied the multi-element distributions for sediments, and particulate materials suspended in the water column which are representative of the Bristol channel-Severn Estuary system, U.K.

The overall geochemistry of bottom-deposited sediments is very similar to that found for mean crustal rocks and reflects the locally available sediments which contain large amounts of well-mixed glacio-fluvial deposits of Pleistocene age. A significant enrichment in some elements, for example, Li, B, C, N, F, Zn, Br, I and Pb was observed for suspended particulates, while an enrichment in

other elements, such as As and Sn may also occur.

The highest levels of enrichment were found in materials containing a large proportion of ferruginous floc enclosing finely divided clay debris.

The upper reaches of the system contain extensive silt and mud banks and about 5 cm below the surface of these sediments anaerobic conditions exist. As a result of tidal movements, supplemented by storm disturbances, anaerobic pore-liquids are released providing a significant flux of elements to the overlying water column. Following release of elements and compounds from bottom waters, subsequent removal through flocculation processes occur of which the iron system is of particular importance.

Fraser River Estuary

It is the largest river (in terms of both water and sediment discharge) reaching the west coast of Canada, and is sand-dominated river in which most sediment transport occurs during freshet in late spring and early summer. More than half the sediment discharged during this 2-3 month period is sand. Throughout the rest of the year, the river is characterised by lower flow and low suspended

sediment concentrations (primarily silt and clay), net offshore transport during these months is slight and near bottom transport appears to be landward (Milliman, 1980).

Although understanding the flow and sedimentology of the Fraser River and its estuary is critical both for scientific reasons and for sound economic development of this river, the Fraser is practically unstudied by geologists, the only published works being on deltaic and offshore deposits (Johnson 1921; Mathews and Shepard 1962; Luternaur and Murray 1973; Pharo 1972).

However, Milliman (1980) has described the river flow and sedimentation within the Fraser, summarised largely from suspended and bed-load data gathered by the sediment survey section of the Water Survey of Canada.

Gironde Estuary (France)

The Gironde estuary is located on the Bay of Biscay, on the Southwest coast of France.

A number of studies in the Gironde (Bonnefille 1971; Migniot 1971; Allen 1972) have analysed the mechanisms responsible for the

transport and accumulation of muddy sediments, and in particular those effecting sedimentation in the main navigation channel.

Allen et al. (1980) suggested that net accumulation of suspended sediment in the macro-tidal estuaries of the French Atlantic Coast is a result of the interaction between tidal and density processes.

Comparison of the Gironde estuary cumulative grain-size curves, expressed as log-probability plots, with the results obtained by Visher (1969) shows that three distinct transport modes can be assigned to the sediments in the study area. Those sediments finer than approximately 3.0 $\phi$ - 1.3 $\phi$ represents the "Saltation" population and sediment coarser than 1.3 $\phi$ - 0.6 $\phi$ denote the "Surface creep" population (Allen et al. 1972).

The Gironde appears to be a relatively "mature" estuary, i.e., it has already filled to a large extent its drowned Holocene river valley. Sedimentation rates are higher than the present rate of transgression. Accompanying this sedimentation, a gradual reduction in flow section has progressively shifted the head of the salinity

intrusion downstream. This has been accompanied by a seaward migration of the turbidity maximum, particularly during high river flow, when density circulation is strong. As a result a greater proportion of fine sediment escapes seaward. This "ageing" process is probably also accompanied by a gradual increase in the importance of tidal processes over density processes (Casting and Allen 1981).

Hudson Estuary (USA)

Sedimentological studies in Hudson estuary and near-shore marine environments have traditionally utilized grain-size, mineralogical and suspended solid measurements. Previous work of this type on the Hudson Estuary includes that of Panuzio (1965) McCrone (1967) and Coch (1976). Panuzio (1965) discussed circulation and siltation processes in the estuary, while McCrone (1967) studied the general lithology and cation exchange capacities of the sediment and found no significant differences in the mineralogical and chemical properties of the sediment with depth or in a downstream direction. Coch (1976) conducted grain-size analyses on sediment and concluded that net deposition is occurring along the entire length of the

salt intruded reach of the estuary. No previous study has described the recent sedimentary structures nor has used data related to the time scale of deposition to determine whether the grain-size or mineralogical studies were conducted on recently deposited sediments or on older sediments exposed by erosion, dredging or on net deposition.

Oslen et al. (1978) carried out the geochemical and sedimentological studies on cores taken out from this estuary. They concluded that the rate of sedimentation is 5 to 20 cm/yr in the inner harbor which is more than two orders of magnitude greater than net sedimentation rates in the channel and more than one order of magnitude greater than on the subtidal banks of the river estuary. The fine-grained material responsible for shoaling in the inner harbor is primarily river-borne.

Lower Thames River Estuary (Connecticut)

Since 1974 the lower Thames River, near New London, Connecticut has been the scene of major dredging efforts intended to increase the depth

of the main navigational channel from 11 to 12 m.

Majority of the investigations concerning dredge-induced suspended material concentrations have placed primary emphasis on the hydraulic dredging process.

In 1973, Gordon detailed the spatial extent of the sediment plume adjacent to a large volume Calm-shell dredge (11 $m^3$ bucket) and showed the plume to be a well defined, relatively small scale feature, extending over a distance of approximately 1000 m downstream. The data indicated that approximately 2.5% of the dredged sediment volume is introduced into the water column adjacent to the dredging point and subsequently advected and dispersed downstream. Deposition of these materials was shown to produce effects equivalent to the sum total produced by the passage of four coastal storms, although the area affected would be substantially smaller.

Bohlen et al. (1979) indicated that the concentrations of the suspended material adjacent to the dredge is from 200 $mgl^{-1}$ to 400 $mgl^{-1}$.

Matanza River (A Microtidal Estuary)

Matanzas Inlet is a natural, unconstructured

inlet which connects the Atlantic Ocean with the Matanzas River-Intracoastal Waterway System on the northeast coast of Florida.

Matanzas Inlet has a spring tidal range of 1.75 m, putting it into the microtidal category (Davies, 1964), but its morphology is that of a mesotidal inlet (Hayes 1975).

Gallivan et al. (1981) concluded that all data indicate that inlet presents an important, but quite localized, influence on open coastal process. Likewise such open coast phenomena as longshore currents have pronounced effects on inlet hydraulics. Significant influence at Matanzas Inlet is restricted to within a few hundred meters of the inlet itself. It is expected that such factors as tidal range, tidal prism, size and shape of the inlet and the ebb delta are factors in determining the extent and nature of influence on coastal processes. By contrast weather conditions and resulting wave climate cause varying influence on inlet processes.

Longshore current direction and its relationship to ebb delta morphology create shadow effects on the down-current side of the inlet.

Mississippi Estuary (N. America)

It is one of the well studied estuaries of the world. It is a delta-front estuary with basin area $3.25 \times 10^6$ sq. Km. and discharge $18 \times 10^3$ $m^3$/sec. (Fairbridge 1980) and annual sediment output $0.5 \times 10^9$ tons (Postma 1980).

A dynamical treatment leading to a method of predicting changes in the breadth, thickness and other properties of spreading plume at the mouth of the Mississippi was carried out by Wright and Coleman (1971). They observed that the plumes extending from the mouth of the Mississippi are 1 m deep and 10 Km. wide.

Prebley and Trefry (1980) compared interstitial and sediment Mn distribution in rapidly accumulating Mississippi Delta sediment with that in deeper water Mississippi Fan sediment. They found that a calculated flux of Mn on the order of 1000 $\mu g\ cm^{-2}\ y^{-1}$ was passing into the overlying water and consequently the bottom sediment had a total Mn concentration ($\sim$ 660 $\mu g/g$) which was about one half that in the particulate flux ($\sim$1300 $\mu g/g$) to the sediments.

Studies on the Mississippi by Bien et al. (1958) suggested that the removal of dissolved silicon during

estuarine mixing is extensive, and in some situations, almost complete. The data of Bien et al. (1958) have been reinterpreted by Schink (1967) who suggested 10 - 20% removal of dissolved silica. Later studies of the Mississippi estuary by Fanning and Pilson (1973) have indicated much lower removals of about 7% of the dissolved silica in river water.

Narragansett Bay Area (Rhode Island)

Three connecting passages, West Passage, East Passage and the Sakonnet River, comprise lower Narragansett Bay, Rhode Island.

It is a partially mixed, two layered estuary with less saline water flowing out of the Bay above more saline water moving into the Bay (Hicks 1959, 1963). Tides in the Bay are semidurnal with a mean range of about 1.3 m (United States Coast and Geodetic Survey, 1973). Although the bay circulation is generally dominated by tidal current ranging from 50 to 140 cm/s (Hicks 1959) wind has a significant influence (Weisberg and Sturgas 1973).

McMaster (1960) mapped the sediments of Narragansett Bay and Rhode Island Sound and found the most abundant sediments in the Bay are clayey silt and sand-silt-clay. In general, sediments in

the Bay become progressively coarser toward all three passage mouths (Collins 1976).

Coriollis acceleration may cause the dextral movement of near surface and near bottom suspensates from the mouth of estuaries (Collins 1976).

Oviatt and Nixon (1975) noticed that the monthly samples of sediments deposited in traps at three locations in Narragansett Bay, showed a gradient in sediment activity that increased from an annual mean of 20 $\pm$ 8.8 $gm^{-2}$ $day^{-1}$ at the head of the estuary to 51 $\pm$ 16.7 $gm^{-2}$ $day^{-1}$ at the mouth. Deposited materials were significantly higher in total organic content.

Northern San Fransisco Bay

During much of the year the northern Bay is a partially mixed estuary with its circulation and salinity responding to variations in river inflow. During winter, salt water induces landward to San Pablo Bay and in summer to Rio Vista. The salt field probably never fully achieves steady-state adjustment with the water circulation even after a period of weeks of near-uniform river inflow. The salinity is generally low in relation to river inflow

during summer and may be high during winter because of the lag in response to salinity to discharge (Ward and Fischer 1971).

Seasonal variations in water chemistry and phytoplankton abundance in San Fransisco Bay Estuary (Peterson et al. 1975a) appear to be closely related to the general water circulation effects on non-conservative (Biological and Chemical) distributions in partially mixed estuaries. They described a steady state numerical model of dissolved silica and applied it to the seasonal silica variations in this estuary, estimating silica-utilization rates which produce nonconservative distributions. They estimated the silica uptake to be 2 μg/at $l^{-1}$ $day^{-1}$. Replacement time is more than 70 days; silica concentrations are well below 70 μg-at $l^{-1}$ from their predicted conservative concentrations and may approach growth-rate limiting levels.

Inflow increases during fall, silica input exceeds removal by phytoplankton and eventually silica-salinity distributions become conservative (linear).

Rupert Bay (Canada) - A Subarctic Estuary

Rupert Bay is a shallow stream-dominated embayment at the head of the large James Bay estuaries system. It is truely estuarine only near its exit, as salt water does not penetrate more than a few kilometers and tidal mixing is insufficient to combine the four incoming river plumes which remain distinct along the whole length of the Bay.

Due to ice unloading and crustal readjustment, at a current rate of 1 m/100 yrs, these rivers have excavated their channels into marine sediments to the early post-glacial Tyrrell sea invasion. These provide the main source of the poorly sorted silty clays forming the present deposits. D'Anglian (1980) observed that the sediment transport and depositionaare influenced by strong seasonal fluctuations in climate.

Sandyhaven Pill Estuary (South Wales)

Sandyhaven Pill is a "drowned valley" type of estuary located close to the mouth of the larger Milford Haven estuary in western South Wales. Thus, the deposits differ from most other described estuarine deposits which are of "tidally influenced river" type. The surface sediments may be divided broadly into wave-dominated deposits (22% of area), tide-dominated deposits (65%), deposits related to marginal

cliff collapse (12%) and river dominated deposits (1%) (King, 1980). Further subdivision shows that the sub-environments are vested in a progression up the estuary with trends to finer sediment size, reduced sorting and increased biogenic activity. The latter relates to a marine to estuarine faunal change and a strong relationship between the distributions of biota and depositional subenvironments.

Seine Estuary (France)

The Seine estuary is funnel-shaped and both the width and cross-sections decrease exponentially up-stream from the mouth. This funnel shape extends land-ward a distance of 30 Km, where the estuary merges into tight meanders of the Seine River.

The mean average discharge of the Seine is 400 $m^3/sec$ (Avoine, 1980). The river flow varies season-ally, from a maximum in January to a minimum in September.

The Seine river supplies a considerable quantity of suspended silt and clay to the estuary. Suspended sediment concentrations were measured regularly during the last 10 years. Avoine (1980) established a mean annual influx of fluvial suspended sediment of 530,000 tons per year (dry weight) which varies with river discharge.

Tidal currents are strong in the Bay of Seine and estuary.

Avoine et al. (1981) pointed out that man-made modifications of the Seine estuary have produced large geometric changes with important hydrographic and sedimentological consequences affecting estuary-shelf interrelationships. The estuary once had shallow, meandering ebb and flood tidal channels and broad tidal flats. Today, after 130 years of landfill, marsh reclamation, jettying and dredging, there is only a narrow, deep, jettied channel extending to the sea. Most of the tidal flats and marshes have been filled.

This change has amplified seaward transport of fluvial suspended sediment and increased the size of shelf mud zones off the estuary mouth. Man has thus changed the geologic role of the estuary from a sink for fluvial and marine sediment, to a source of fluvial sediment of the shelf.

Shatt-Al-Arab Estuary (Iraq)

It is a very important estuary for the fisheries-economy of Iraq and Iran. Only a very few studies were carried out on the water of Shatt-al-Arab (Mohammed, 1965a,b; Al-Saadi and Arndt 1973; Arndt and Al-Saadi 1975; Kell and Saad 1975). Saad (1978)

carried out some physical and chemical investigations of Shatt-al-Arab estuary. He observed that the transperancy as well as the average values of suspended matter generally show local and seasonal variations. The slight decrease of water temperature with depth is related to the mixing processes. The relatively high average pH values found in August and October give a good evidence for the phytoplankton abundance in better environmental conditions.

The slight local variations in the Average values of chlorinity generally observed in each season mainly coincide with the flow of the freshwater of this estuary.

St. Lawrence Estuary

This is a much studied estuary. On the basis of the definition of an estuary given by Pritchard (1967), the St. Lawrence estuary begins at the upper limit of the salt water intrusion near Quebec city and may be extended to 400 Km downstream to Pointe-des-Monts, where its channel suddenly opens up into the Gulf.

A natural subdivision into an upper and lower estuary is suggested by the bottom physiography.

D'Anglejan and Smith (1973) studied the distributaries transport and composition of suspended matter and concluded that the concentration varied from nearly 40 mg/l below near Ile d'Orleans to values less than 1 mg/l at the downstream end of the upper estuary near the Sanguangy River entrance. The clay mineral composition of less than 2 u x fraction is on the average 1.5% montmorillonite, 8% Kaolinite; 31% chlorite and 60% illite. He observed that large time and space variations are found both in the chemistry and mineralogy of the suspended matter.

Subramanian and D'Anglejan (1976) studied the water chemistry and maintained that it is mainly carbonate type.

D'Anglejan and Brisebois (1978) observed that little deposition takes place at present in the St. Lawrence middle estuary. They maintained that the muds were formed under a different sedimentation regime in which deposition from suspension must have been dominant.

D'Anglejan et al. (1981) while studying the suspended sediment exchange between the St. Lawrence estuary and the coastal embayment observed fluctuations in exchanges with the main estuary, which help maintain

material balance over long-term periods which are modulated by the run-off intensity. They have strong seasonal component with export dominating import in late winter and spring and the reverse in summer. The fortnightly tidal cycle also seems to play an important role in these exchanges. Yeats and Bewers (1982) studied the discharge of metals from the St. Lawrence river and observed that the variability in the concentrations of dissolved metals is unrelated to changes in water flow or suspended load. Particulate Al, Fe, Mn and Zn concentrations are related to water flow. The metal/aluminium ratios of particulate Mn, Cu, Zn and Cd are elevated with respect to crustal rocks or coastal marine sediments, with the enrichment occuring in the non-detrital or weak acid soluble, fraction.

Tamar Estuary (South-West England)

As a part of the estuarine geology programme of the Natural Environment Research Council, Morris (1978) studied the interaction chemical processes in the Tamar estuary.

He maintained that a dominant factor in determining the pH distribution within the estuarine system at any time is the pH of the freshwater source. This remained relatively constant throughout the course of

each separate investigation, but large seasonal differences in freshwater pH were found. He emphasized that the overall pH-salinity relationship is also dependent on the total alkalinity of the fresh and sea water, temperature, and the pH of the sea water. But, none of the results obtained for the Tamar estuary conforms with this predictive model (Morris 1978).

Tees Estuary

It is a relatively narrow and winding estuary which discharges into the North Sea off the north-east coast of England. The Tees Estuary is heavily industrialized and extensive studies have been reported on the effects of domestic and industrial wastes (Hobbs 1970). A sophisticated mathematical model of the estuary has been developed to make predictions of pollutants distributions (Hobbs and Fawcett 1972), and this model has been verified by a detailed survey of conditions along the estuary axis. Since the Tees is relatively narrow and is partially stratified, only variations along the axial and vertical directions were modelled.

The tides at the mouth of the Tees are predominantly semi-diurnal and have mean spring and neap ranges of 4.6 m and 2.3 m respectively (Lewis 1974).

The average freshwater discharge is only about 2.8% of the total volume flow through the mouth on an ebb.

Analysis of the velocity data suggested that lateral changes in the vertical gravitational circulation contributed to the net transverse circulation. The depth mean salt fluxes per unit width associated with transverse deviations from the cross-sectional means of the steady and tidal flows showed appreciable variation across the estuary, particularly where there were marked changes in the topography (Lewis 1979).

In India

The Indian rivers can be grouped under two headings, Peninsular and extrapeninsular. We have the easterly drainage of the Peninsula exceptions being Narmada and Tapti, which drain into the Arabian Sea.

Both types of rivers differ in their physiography, erosion and deposition. Western Ghat rivers do not have delta formation at their mouths because the strong coastal currents and tides disallow the deposition to take place. On the other hand, the debouchers of these streams are broad deep estuaries daily swept by the recurring tides. Quite contrary to it, the East coast rivers not only participate in erosion and

transportantion of sediments but they do active depositions also. The Ganges delta is only 5000 years old (Wadia 1953).

Only in recent past, the chemical, physical, biological and sedimentological studies of Indian rivers have drawn attention of workers, in order to understand the overall nature and environment.

All the rivers drain into the ocean via estuary. So, to study all the aspects of the estuary becomes important for better understanding. Though, a number of works have been done on Indian rivers by many workers (Ramahashaya 1970; Handa 1972; Subramanian 1978, 1979, 1980, 1982; Subramanian and Dalavi 1978; Bikshamaiah 1980; Abbas 1982), but not much work has been done on the estuary and its environment. Literature on Indian estuary and deltaic region are very few (Naidu 1966; Rao 1966; Siddique 1967; Chakraborti 1968; Sarma and Ganapati 1968, 1969; Mallick 1976; Borole et al. 1977).

In an attempt to study the trends of sedimentation in and around Godavari delta Rao (1966) observed that the Kakinada Bay is mostly occupied with silty clays. He recognized three heavy mineral provinces, Mica province, Hornblende province and a Garnet-Sillimanite province. He noticed high organic carbon content in the tidal flats along the western side of the bay.

Sarma and Ganapati (1968) studied the hydrography of the Kakinada Bay and concluded that the seasonal changes in temperature is largely governed by the atmospheric changes. Thermal stratification attended by the salinity stratification was noticed during the period of heavy drainage from the head of the bay and the Kakinada canal. Taking several factors into account they concluded that pattern of net water movements within the bay seemed to be clockwise from December to June and anticlockwise from July to November.

Coringa river (a part of the Gautami-Godavari Estuarine system) is characterized by low transparency of the water through a greater part of the year; prolonged period of freshwater inundation; salt water incursion from both the ends beginning from November, steep horizontal and vertical gradients in salinity and temperature; high nutrient concentration during the summer season, and inflow and outflow of water during the flood and ebb phases of the tides respectively (Sarma and Ganapati, 1969).

Naidu (1966) has done studies on the delta region of the Godavari River and found mineralogical differences between freshwater and estuarine water sediment

(freshwater-kaolinite 36-48%; illite 17%;(Na + Ca) montmorrillonite 18-36%; Saltwater-kaolinite 14-40%; illite 20%; Na-montmorillonite 45%; chlorite 20%).

Siddique (1967) reported illite, kaolinite and some montmorillonite from the Bay of Bengal sediments. Mallik (1976) has studied the mineralogy of the sediments of the western part, Bay of Bengal and noticed that the mineralogy of the core samples in the top and bottom layers does not differ, indicating that the source area remained the same during the time of their deposition. Depending on the mineral assemblage, he concluded that the Hooghly river province, is characterised by consisting of hornblende, tremolite/actinolite, epidote and garnet. He further emphasized that the illite and kaolinite are the typical clay minerals in the sediments. The mineralogical grain size, and the lithogenic studies of the sediments from the core samples suggest a southward to south-southwestward direction of dispersals of the sediments in the eastern part of the Area.

Mallik (1978) while studying the Ganges cone sediments noticed that they consist of alternating silt, silty sand and clayey silt interbedded with nanno oozes.

Borole et al. (1979) carried out a preliminary investigation on dissolved uranium and silicon and major elements in the Mahanadi estuary. They reported that U-isotopes show a nearly conservative behaviour. The $^{234}U/^{238}U$ activity ratio in the freshwater end member appears to be inversely correlated to the $^{238}U$ concentration which can be understood in terms of leaching of the suspended material. They observed that in the low chlorosity region (0-1 g/l) the Si concentration show a large variation by about a factor of two irrespective of the season. Between the chlorosity range of $\sim$ 1 to 14 g/l, the winter Si values are lower (by $\sim$ 50% to a factor of $\sim$ 3) compared to the summer Si values. Na, K, Ca and Mg were found to behave conservatively in the Mahanadi estuary during both the winter and summer seasons.

The Hooghly estuary is a part of the large estuary of the Ganges-Brahmaputra system. Due to political as well as geographical location of this estuary, it has not been fully studied. The only paper produced on the Hooghly estuary is that of Bhattacharya and Ghotankar (1968), which does not provide much information.

From the above brief review it is clear enough that the Hooghly estuary which is the largest (both in area and sedimentation rate) estuary of India has not been studied at all. The Hooghly being the urbanized estuary is also important for the navigational and economic point of view. The work done so far is restricted upto Calcutta only, not beyond that. So in order to understand the various aspects of the water and sediment chemistry an attempt is being made in this study.

# CHAPTER - II

## A BRIEF DESCRIPTION OF THE HOOGHLY ESTUARY

### HISTORICAL REVIEW

The Ganga and the Brahmaputra are the important rivers which form the Gangetic delta covering a triangular area of about 64,000 sq. km. with Hooghly river on the west, the Meghana and Chittagong coast on the east, and the apex between Rajmahal and Rampur Baolia. The Bhagirathi, Jalengi and Churni take off from the Ganga to form the Hooghly (Bhattacharya and Ghotankar 1968). In the downstream, Damodar, Rupnarayan and Haldia also join the Hooghly river. Besides these some smaller tributaries also contribute their water and sediment supply to this main channel as shown in Fig. 1.

The Hooghly estuary is a part of the Ganges basin (861404 sq. km; Abbas 1982). According to the water discharge (459040 million cubic meter, Rao 1975), it is the fifth largest river of the world, but in terms of the sediment yield it is the second largest (Holeman 1968). At Rishikesh the Ganga descends to the plain. From Tribeni, of the three branches,


Fig.1.MAP SHOWING THE HOOGLY ESTUARY AND SITES OF SAMPLING.

Map taken from Calcutta Plate 33. Govt. of India (1959)

SCALE

10 0 20

1 m.m = 1 km

the middle-branch - the Bhagirathi - flows down to the present course of the Hooghly (Bhattacharya and Ghotankar 1968).

Like the changes in the Ganga course, the changes in the Hooghly estuary also have been observed (Bhattacharya & Ghotankar 1968), e.g. in the 1930s the river section in the neighbourhood of the outfall of the Haldia river was all under water even at low springs. Since then the eastern bank line eroded and a central island gradually developed, so that under present conditions a large island called the "NAYACHARA" has developed with a channel on either side (Bhattacharya & Ghotankar 1968). Prior to this, there has been erosion of the Western bank at Ganga as also at the Southern face of the Sagar island.

Geology :

The Bengal basin is delimited by the Peninsular Shield with interactonic Gondwana basins and Rajmahal Traps on the West, by the Shillong Plateau on the north east, and Naga-Lushai Orogenic belt on the east. The

Garo-Rajmahal gap separates the Peninsular shield from the Shillong Plateau. The sedimentary fill occurring north of the Garo-Rajmahal gap perhaps represents a part of the foredeep or crustal downwarp believed to have been formed in response to the Himalayan Orogeny. Information about the sub-surface geology of this foredeep is rather inadequate.

The Peninsular Shield disappears below a thick pile of sediments ranging in age from Cretaceous to Recent, the thickness of which increases South-eastwards (Biswas 1959-63). Chattèrjee et al (1959) have recorded the top of probable Tertiary sediments at shallow depths of about 80 m. Structural profiles of the Bengal basin, as deciphered by Sengupta (1966) show the occurrence of a number of buried basement ridges, a row of basin margin faults and the stable shelf of the Bengal Basin in succession from West to East.

The structural downwarp is reported to occur around Calcutta, east of which the basin deepens with a marked change in lithofacies from arenaceous stable shelf facies on the west to

argillaceous geosynclinal facies on the east. A thick cover of Quaternary sediments conceal these sub-surface geological features.

Physiography

The area lying between the branching of Padma and Bhagirathi in the north to the Bay of Bengal is a part of the Ganga delta which has built up its present form by receiving sediments from river systems of both the Ganga and the Brahmaputra. The northern extremity of the area has an altitude of about 135 m above sea-level while that of the South is about 9 m indicating that the area has a general southward land surface gradient. In Nadia and Murshidabad districts the delta has become Moribund. The channel in this region have shown signs of decay due to the eastward shifting of the Ganges from a main outlet along the Western margins - the Bhagirathi, Hooghly to the present main courses, the Padma - Meghana. The Jalengi and Churni flowing through the Nadia district are the two main decaying rivers within this moribund area. Whether these changes are due to alluviation at

the heads of successive main spillways, or to tectonic changes or to shifts in the balance of the delta due to changes of course elsewhere (e.g. the great shift of the Teesta) or to a secular swing to the east, are questions which admit of a large and inconclusive debates. It is, however, clear that the Bhagirathi, or its branches like Hooghly, Saraswati, Adi- Ganga or Tolly's Nulla were the most important distributaries in the 17th century, but have been silting at least since 1770, when the Damodar which helped to keep it clear, shifted its mouth 128 Km. to the South (Bull. G.S.I.; series, B;N. 34:1973). The literature on the hydrographic changes in this region records that during the later half of the 17th century, the Damodar was debouching both into the Rupnarayan and the Bhagirathi; by means of two branches, the larger one running south-east to meet the Rupnarayan while the smaller one ran east to meet the Bhagirathi. According to still older maps of the 16th century, Rupnarayan itself was discharging by two channels enclosing at its mouth

a large island. The south eastern branch probably disappeared during the middle of the 17th century, which resulted in connection of the island with the mainland.

The region between the moribund delta and the Sundarbans which falls within the northern half of the 24-Pargana may be considered as matured delta. In this region the rivers are more "live" and some silting occurs along the larger one. The region has a monotonous, more or less flat topography with a very gentle slope towards south. The active delta consists mainly of the Sunderban.

The great tidal mangrove forests stretch along the surface for about 270 Km. and reach 96-128 km. inland. The area is very flat, swampy and mostly in level with the sea.

There is some debate as to whether the delta is still advancing seawards or whether it is losing by marine erosion more than it gains. Local erosion, no doubt, exists but on the whole it would seem that local accretion predominates. The building up of new land has to be slow, as the supply of silt from the land is

limited. The recent emergence of many new islands near the coast indicate the phenomena of local accretion within the deltaic region.

Climate and Rainfall

The most prevalent climate of the area is tropical, hot and humid.

Incidence of rainfall is maximum during the monsoon months (June to September) averaging about 175 cm/yr.

Tides and Currents in the Hooghly Estuary

There is indication of two-tidal waves approaching the Hooghly estuary - one from the south-east side and another from the south-west side, so that at Sagar island the wave crest is practically east-west (Bhattacharya & Ghotankar 1968). This, however, is only a rough approximation and needs further observations and analysis.

The data of Ganges (taken by Calcutta Port Commissioner) show that as one proceeds from the surface up the estuary, the ranges increase gradually by about 10 % to Hooghly Point in a distance of 4.6 nautical miles. Beyond this, in a distance of 34 nautical miles up to Calcutta it reduces by 14% and the rate of reduction of range

increases rapidly beyond a few miles above Calcutta.

The currents also show sympathetic variation. In the outer estuary the currents are of a rotary nature (Bhattacharya & Ghotankar 1968). Up the channel the maximum flood currents increase, reaches a peak and then gradually reduces (Fig. 2) The rotary nature of the currents in the outer estuary, the direction of waves and the coriolis force have a combined effect in orienting the sands in a sickle shape.

The Outer Estuary of the Hooghly

North of the Dhamra estuary (Lat. $20^{o}$ 47') the coast line of the Bay of Bengal runs in an approximately north-west direction and curves round gradually north of Lat. $21^{o}3'$ to run in an east-north-east direction to the Hooghly estuary. Between latitudes $21^{o}40'$ N and $25^{o}25'$N and along the longitude $87^{o}47'$ runs a Shoal ridge known as the "Western Seaf Reaf" (fig. 3). This ridge approximately forms the Western boundary of the outer estuary of the Hooghly. From Kankhali Light House, (Lat. $21^{o}10'$ N, long. $88^{o}3$-1/2') runs another shoal ridge known as "Eastern Sea Reef".

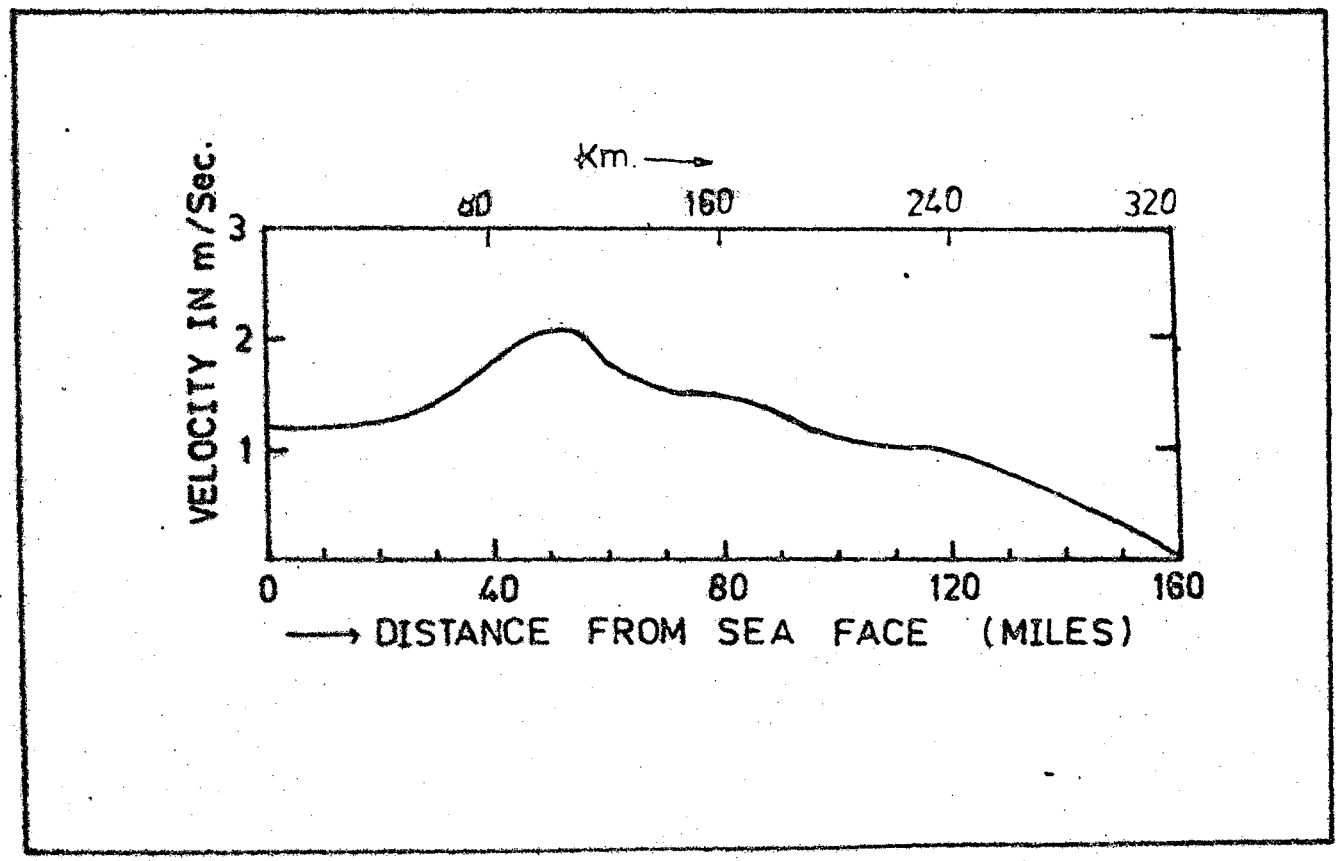


Fig.2. Flood velocity distribution along the river Hooghly.

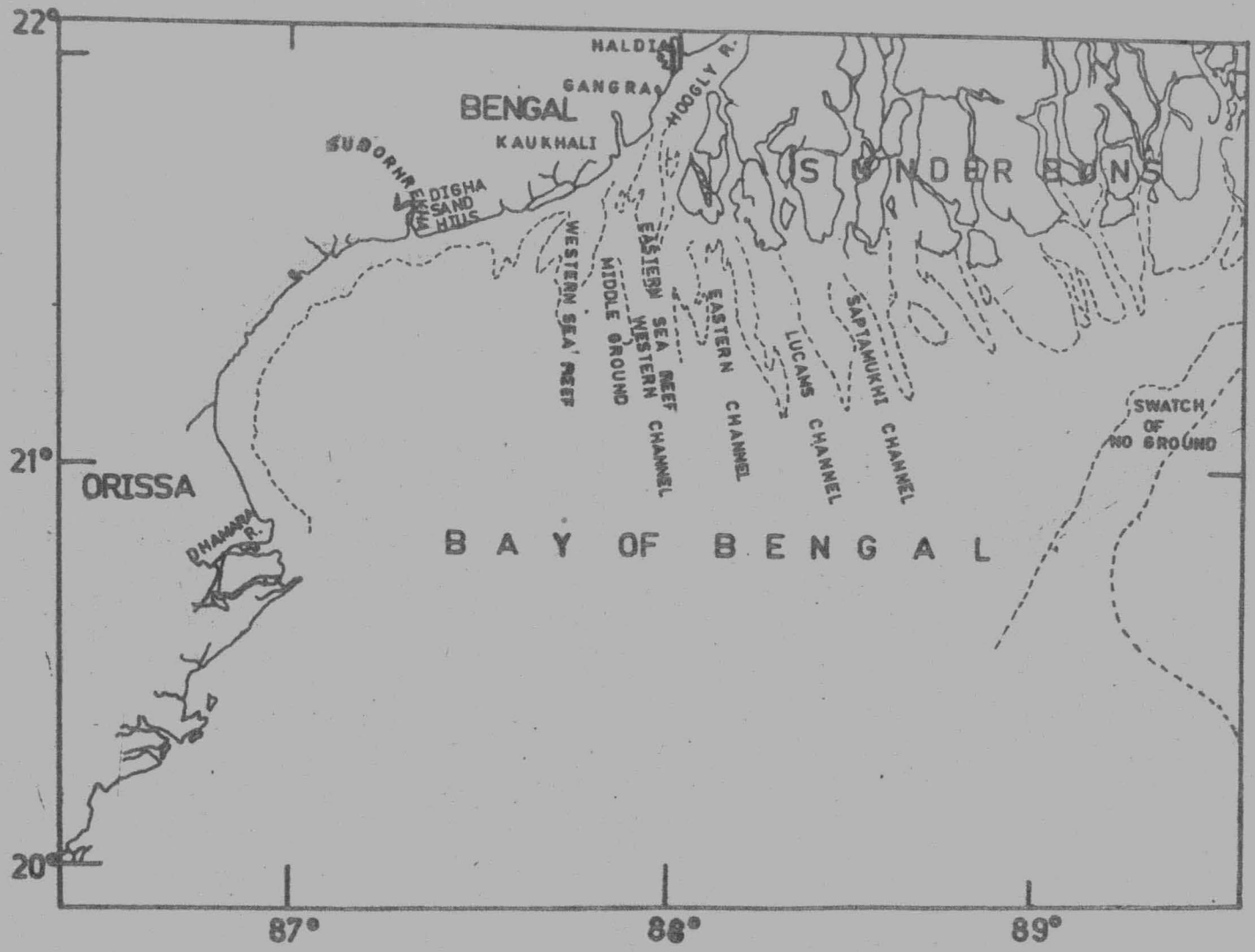


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Fig. 3 Outer estuary of the Hooghly

Between the two reefs is the shallow middle ground. On the east of the Eastern sea Reefs runs the Eastern channel which is one of the relatively stable approach channels to the port of Calcutta, while on its west runs the Western channel. Further, eastwards of the Eastern channel run ridges with interspersed channels leading to the various Sunderban creeks. All the ridges generally run in a direction few degrees east of due south. Further to the east, a deep submarine valley known as "the swatch of no ground", runs in a north-easterly direction. The configuration of the ridges and the channels is governed by the tidal currents and waves which influence the sediment movement and currents.

The funnel-shape of the Hooghly is well suited for the optimum tidal flux which is the prime factor governing the channel regime and the navigability to the port of Calcutta.

# CHAPTER III

## FIELD AND LABORATORY METHODOLOGY

### SAMPLING PROCEDURE

Sampling for both the surface water and the bed sediments from the same point were done during February 1982. Approximately one litre of surface water containing suspended sediments were collected in the polythene bottles on each side of the Hooghly estuary starting from Chuchure to Digha (200 Km.). Samples for both the surface water and bed sediments were taken from different locations, so that they can represent riverine, mixed and oceanic environment.

The pH and bicarbonate content of the surface water was measured on the spot. All the samples were packed air-tightly and labelled and sent to the laboratory, where they were kept in the cold room (temp 3°C) in order to avoid organic decay. The sampling locations are given in Fig. 1.

### Water Analysis

The pH, conductivity and alkalinity of each samples was done immediately after its arrival in the laboratory.

The filtered water samples from all the stations were analysed for various elements present in the system. The detail description of methods adopted are furnished below:

pH

The pH of water samples was measured by Elico pH meter model LI-10T; for precision of results and its variation from the field measured pH was also taken into account. The instrument first, set for standard pH 7 buffer at temperature 23°C and then the samples pH was taken. The cross-checking was also done.

Conductivity

Specific conductivity of the samples in mMHO/cm was measured with a systronic® direct reading conductivity meter-303. First the instrument was callibrated and set for 0.1 KCl standard. The measurement was made at 23°C.

Chloride

The method adopted for the chloride determination is after Ford & Deeveg Jr. (1946).

At first the standard solutions of chloride of various concentration were made. These were titrated with silver-nitrate solution (concentration 0.01 N). Then, the samples were titrated with the same concentration of silver-nitrate solution. Cross-checking was also done. Potassium chromate ($K_2CrO_4$) was used as indicator. A standard graph was plotted against the concentration of standard chloride and volume of silver nitrate consumed. From this graph by the method of interpolation the concentrations of chloride in the samples were determined. The standard plot of this graph is given in the appendix.

Bicarbonate

The bicarbonate was determined in the laboratory by following the potentiometric titration method.

The estimation of bicarbonate content was done in the field by titrating the standard solution of bicarbonate with 0.02 N Hydrochloric acid using methyl orange as an indicator. A

standard graph was plotted for the volume of HCl consumed against various standard strengths of bicarbonate solution. The concentration of bicarbonate content in the samples were measured by comparing their readings with the standard graph.

In the laboratory, soon after the arrival of water samples, bicarbonate content was estimated. This time no indicator was used but instead the pH of samples as well as that of standard solutions were maintained at 4.5 to signify the end point, by adding HCl (.02N) acid. The graph was plotted as earlier and the bicarbonate concentrations measured.

The average value of bicarbonate content obtained by these two methods was considered and used in this text.

Silica

The silica content was determined by the Molybdo-silicate Method (Hem 1959).

Standard solutions of 0.5, 1, 2.5, 5.0 and 10.0 ppm $SiO_2$ were prepared by dissolving $Na_2SiFe$ by diluting the sample in various proportions. 25 ml of each standard and water samples were used in titration.

In each samples, 10 ml ammonium molybdate solution (the solution was prepared by dissolving 2 gms. of ammonium molybdate in 10 ml of distilled water and adding 6 c.c. of conc. HCl acid and the total volume is made to 100 c.c. by further diluting it with distilled water) and 15 ml of reducing reagent was added (prepared by mixing 100 ml metal sulphate solution, 60 ml of 10% oxalic acid and 120 c.c. of 25% sulphuric acid and making the total volume 300 ml by adding distilled water. Metal sulphate solution was prepared by dissolving 5 gm. of metal in 210 ml of distilled water. Again 3 gms. of sodium sulphite was added and dissolved and distilled water was added to make the volume 250 ml).

The samples were stirred properly and kept for 3 hours to let the reaction complete. The optical density was measured for standard and water samples at 812 mμ using Beckman model 34 spectrophotometer. A standard graph was plotted for standard silica concentrations versus optical density (absorption). The silica in the water samples were estimated by comparing their optical density values with the standard graph.

Sulphate

Sulphate was determined by direct titration with barium perchlorate in 80% ethanol with thorin as the indicator. The sample was pre-treated by passing through an ion-exchange resin to remove interfering cations and the titration was carried out in 80% ethanol to keep the barium sulphate in solution.

Reagents

Anala R absolute ethanol

Thorin solution, 0.2% w/v

0.2 g of thorin (di-sodium salt) was dissolved in deionised water and the volume was made 100 ml.

Hydrochloric acid, 10% v/v

Sulphuric acid, 0.005 M.

Perchloric acid - Anala R perchloric acid ($HClO_4$, S.G. 1.66)

Cation exchange resin

Dowex 50 W - X820-50 mesh resin.

Standardised barium perchlorate in 80% ethanol 0.005 M

2.0 gm. of barium perchlorate ($Ba(ClO_4)_2 . 3H_2O$) was dissolved in 200 ml. of deionised

water in a 1 litre beaker and 800 ml of ethanol was added. The pH was adjusted to 3.5 by adding perchloric acid dropwise. 10 ml of 0.005 M $H_2SO_4$ was taken in a conical flask and 40 ml of ethanol and 4 drops of thorin solution were added. In a burette 25 ml. of barium perchlorate solution was taken. The initial burette reading was noted and barium perchlorate with constant swirling was added till the solution just turned from yellow to pink. The final reading was recorded. This step was repeated 3-5 times. Then by the following formula the molarity of barium perchlorate was calculate

$$\text{Molarity of } Ba(ClO_4)_2, \text{ M} = \frac{10 \times \text{molarity of } H_2SO_4}{\text{Volume of } Ba(ClO_4)_2}$$

Sulphite Standard Solution, 1000 mg/l

1.4787 g. of sodium sulphate was dissolved in deionised water and was diluted to 1 litre. From this by proper dilution standard solutions of various concentrations were made.

Method

An air-free ion-exchange column was prepared. In order to activate the resin 30 ml of

10% HCl acid was passed through the column. After that it was rinsed by the 100 ml distilled water. Then approximately 70 ml of unacidified standard and sample was passed down the column. The first 40 ml of sample and standard was discarded and then rest were collected for the analysis. The 10 ml of treated sample were taken into a conical flask and 40 ml of ethanol and 4 drops of thorin were added. In the burette 0.005 M barium perchlorate solution was taken. The inital burette reading was noted and then barium perchlorate was added to the sample with constant swirling of the flask until the solution changed colour from yellow to pink. The burette reading was recorded when the first permanent colour change occurred.

The column was regenerated after every three or four samples by passing 10% HCl and rinsed thoroughly.

Then a graph for standard sulphate solution was prepared, from that the samples sulphate concentration was inferred.

The sulphate analysis as mentioned above is after Fritz & Yamamura (1955) and Haartz et al (1979).

Phosphate

The phosphate was determined by the Ascorbic Acid method.

Phosphate standard solution of different concentration ranging from 0.01 ppm to 1 ppm were prepared from potassium dihydrogen phosphate ($KH_2PO_4$). Four ml from each standard solution and water samples were pipetted out into a 100 ml volumetric flask and 5 ml of molybdate solution and 2 ml of ascorbic acid solution was added and mixed well. The mixture was diluted to 100 ml and extinction was measured at 882 mu by Bausch and Lomb's spectrionic mini 20 after 10 minutes. Molybdate solution was prepared by dissolving 4.8 gms of ammonium molybdate ($(NH_4)_6Mo_7O_{24}.\ 4H_2O$) and 0.1 gm. of sodium antimonyltartrate ($NaSbOCuH_4O_6$) in 400 ml of $4N\text{-}H_2SO_4$ and making the total volume upto 500 ml. With the same sulphuric acid, Ascorbic acid (about 0.1 M) was prepared by dissolving 2 gm of ascorbic acid in 100 ml water. This solution is usable for one week if kept in refrigerator.

Sodium and Potassium

Sodium and potassium were analysed by Carl Zeiss AAS-I spectrophotometer in emission mode. From the standard graph estimation of sodium and potassium of sample water were determined.

Calcium and Magnesium

Calcium and Magnesium were analysed in absorption mode by Carl Zeiss AAS - I spectrophotometer. Various standards of calcium and magnesium were run and values were plotted in standard graph. The values of the water samples were compared with standard graph to get the concentration of magnesium and calcium

Total Suspended Matter (TSM)

Since, the amount of the total suspended sediments was little, it was collected by the decantation process. For this nearly one litre of the water sample was left undisturbed for a week, so that all the suspended sediment may settle on the bottom of the jar. Then slowly, the water was decanted out. When the small amount of water was left in jar, it was transferred in a beaker for drying. The samples were dried

on the water-bath till a constant weight was achieved. However, the possibility of losing some TSM, in the decantation method cannot be ruled out.

## BED-SEDIMENTS ANALYSIS

### Mineralogy

The X-ray slides were prepared from the bed-sediments by "drop on slide" technique (Gibbs 1967) after removing the organic contents. The X-ray diffractograph were taken by Phillips X-ray Diffractometer using CuK radiation and Ni filter. The chart drive was 1 cm/min and intensity 2 x $10^2$. The minerals identification and thdir abundances were done by following the methods of Biscaye (1965) and Carrol (1970).

### Grain-Size Analysis

After removing the organic contents of the sediments by treating it with hydrogen peroxide, they were oven dried. Then they were sieved for 15 minutes on a ILM Labor sieve - shaker using 1/2$\phi$interval Endecotts test sieves. The retent on each sieve was weighed on a Mettler balance. The graphic measures (Folk and Ward 1957) were calculated for each sample from the cumulative frequency curve data.

## Organic Contents Of the Sediments

After taking the dry weight of the samples they were treated with hydrogen peroxide and dried over steam bath, till a constant weight achieved. The difference of weight was noted down, which constituted the total organic content of the sediment.

# CHAPTER - IV

# RESULTS AND DISCUSSION

## WATER CHEMISTRY

The chemical composition of the Hooghly estuary water is given in the Table 1.

### pH

pH varies from 8.5 to 8 (Fig. 4). The short-term control of pH in natural aqueous systems is dominated by the carbonate equilibria. Mook and Koene (1975) have predicted that as a result of the influence of salt content, particularly on the activities of bicarbonate and carbonate ions, pH in the mixing region of estuaries will not show a regular transition between the fresh and sea water. The overall pH salinity relationship is also dependent on the total alkalinity of the fresh and sea water, temperature and pH of the sea water. Figure 4 clearly shows that the pH variation is not systematic. However, the pH generally decreases downstream. This may be due to the fact that downstream the influence of the sea water may be dominant. Subramanian (1979) reported that the alkalinity increases downstream for all the Indian rivers, independently of basin characteristics. He, further observed that the $HCO_3^-$ concentrations

TABLE 1: CHEMICAL COMPOSITION OF THE HOOGHLY ESTUARY WATER (February, 1982)

| Sample Locations Arranged in Increasing Salinity (their distance in Km. from Chuchura is given in bracket) | pH | Conductivity mMHO/cm | Concentration in ppm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Cl^-$ | $HCO_3^-$ | $SO_4^{--}$ | $PO_4^{---}$ | $SiO_2^o$ | $Ca^{++}$ | $Mg^{++}$ | $Na^+$ | $K^+$ | TDS | TSM |
| Chuchura (0) | 8.5 | 0.5 | 18 | 250 | 35 | 0.05 | 7.3 | 35 | 15 | 41 | 1 | 402 | 55 |
| Eden Garden (37) | 8.4 | 0.5 | 18 | 250 | 25 | 0.03 | 7.8 | 125 | 15 | 75 | 1 | 517 | 160 |
| Bauria (55) | 8.4 | 0.4 | 18 | 231 | 35 | 0.03 | 6.3 | 90 | 15 | 90 | 1 | 486 | 950 |
| Budge-Budge (60) | 8.4 | 0.4 | 18 | 240 | 25 | 0.02 | 7.8 | 85 | 14 | 70 | 1 | 461 | 1490 |
| Dakshineswar (26) | 8.4 | 0.5 | 22 | 213 | 25 | 0.03 | 7.3 | 115 | 20 | 80 | 4 | 486 | 76 |
| Bellur (30) | 8.4 | 0.4 | 24 | 245 | 30 | 0.03 | 7.3 | 85 | 15 | 75 | 1.2 | 482 | 300 |
| Howrah (35) | 8.4 | 0.5 | 24 | 231 | 25 | 0.05 | 7.8 | 115 | 20 | 100 | 4.4 | 527 | 250 |
| Kukrahati (91) | 8.3 | 2.2 | 530 | 255 | 100 | 0.06 | 6.3 | 55 | 45 | 90 | 4.0 | 1085 | 260 |

contd....

TABLE 1: CHEMICAL COMPOSITION OF THE HOOGHLY ESTUARY WATER (February, 1982)

| Sample Locations Arranged in Increasing Salinity (their distance in Km. from Chuchura is given in bracket) | pH | Conductivity mMHO/cm | Concentration in ppm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Cl^-$ | $HCO_3^-$ | $SO_4^{--}$ | $PO_4^{---}$ | $SiO_2^\circ$ | $Ca^{++}$ | $Mg^{++}$ | $Na^{++}$ | $K^+$ | TDS | TSM |
| Diamond Harbour (90) | 8.3 | 2.7 | 680 | 210 | 145 | 0.04 | 5.0 | 100 | 60 | 110 | 5 | 1314 | 290 |
| Haldia (120) | 8.2 | 8.0 | 3400 | 200 | 455 | 0.05 | 4.0 | 115 | 285 | 1700 | 23 | 6181 | 1960 |
| Kuchuberia (132) | 8.1 | 14.0 | 5600 | 240 | 895 | 0.05 | 3.0 | 165 | 480 | 3700 | 40 | 11123 | 1500 |
| Kakdwip (130) | 8.1 | 14.5 | 6100 | 158 | 950 | 0.07 | 3.0 | 185 | 740 | 4000 | 40 | 12176 | 430 |
| Namkhana (140) | 8.2 | 19.3 | 8391 | 170 | 1400 | 0.3 | 2.0 | 273 | 820 | 5600 | 55 | 16711 | 1240 |
| Ganga Sagar (165) | 8.0 | 22.0 | 9800 | 140 | 1750 | 0.04 | 1.1 | 297 | 960 | 6400 | 63 | 19411 | 2070 |
| Bakkhali (150) | 8.0 | 26.5 | 12600 | 145 | 2000 | 0.05 | 0.6 | 273 | 1080 | 7300 | 85 | 23484 | 450 |
| Digha (200) | 8.0 | 27.2 | 12800 | 126 | 2000 | 0.05 | 0.6 | 398 | 1200 | 7600 | 85 | 24210 | 1430 |

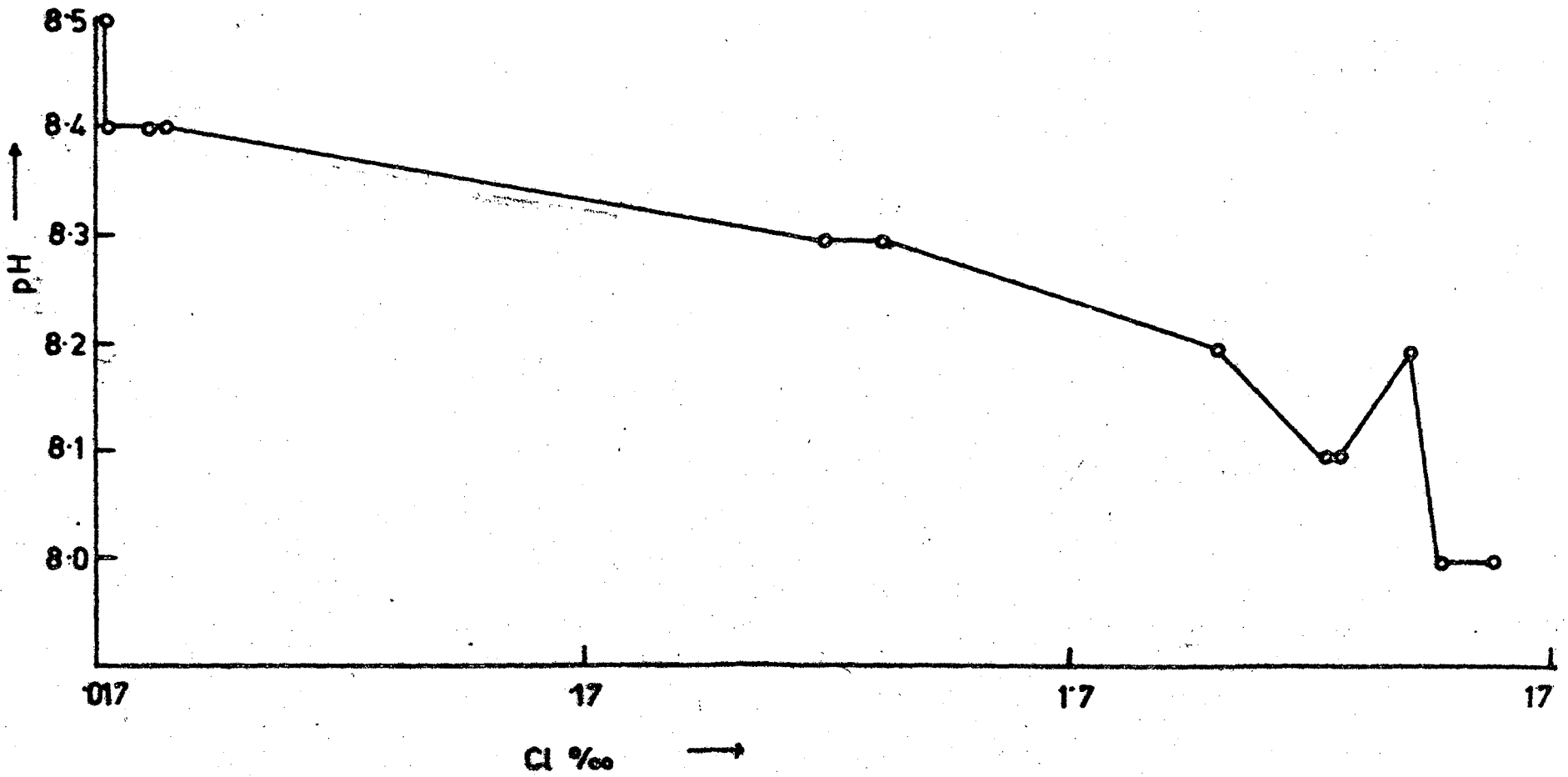


Fig.4. Variation of pH with chlorinity.

are uniformly high and the observed pH's are higher than the theoretical values based on alkalinity, implying that additional pH-buffering mechanisms operate in the Indian river system. But, in the Hooghly estuary, we find that the pH decreases downstream and becomes 8 at Digha. However, the possibility of additional pH-buffering mechanism cannot be ruled out. Morris et al. (1982) observed in the Tamar estuary that towards the seaward boundary, the pH values are in the range of 8-8.2. Borole et al. (1979) also got the same range of pH in the Mahanadi estuary. And, the pH observed at Namkhana, Ganga Sagar, Bakkhali and Digha (at sea coast) are similar to that of the Tamar and Mahanadi estuary.

Conductivity

The specific conductivity shows a sharp increase downstream from 0.5 mMHO/cm at chuchura to 27.2 mMHO/cm at Digha (Fig. 5). In the upper reaches of the Hooghly the conductivity is low (0.4 - 0.5 mMHO/cm) signifying that, this region (from chuchura to Budge-Budge) has fresh water character. From Budge-Budge onwards upto Haldia the conductivity ranges from 2.2 mMHO/cm to 8 mMHO/cm, showing that in this region the mixing of the sea water and fresh water, is pronounced. From Haldia onwards the conductivity shows a gradual

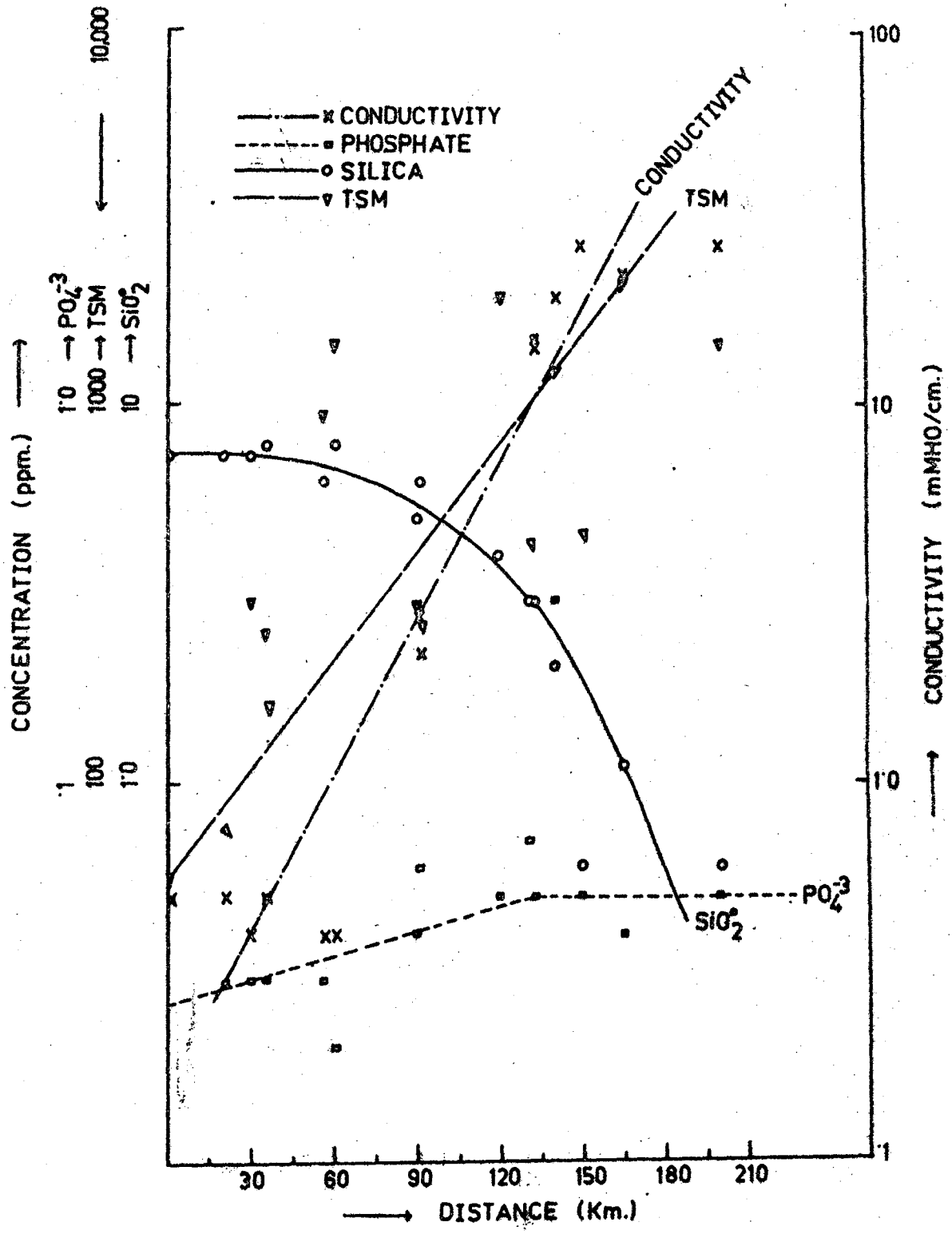


Fig.5. Variation of conductivity, Phosphate, dissolved silica and TSM along distance.

increase from 14 mMHO/cm to 27.2 mMHO/cm, because of the dominance of sea water in the mixing. But even at Digha, which lies on the sea coast the conductivity is much lower than that of pure sea water. Perhaps, the Subarnrekha and Contai canal water, dilute seawater at Digha and lowers its conductivity.

Chloride

In the uppermost reaches, i.e., from chuchura to Budge-Budge the chloride varies from 18 to 24 ppm, signifying the fresh water character of the region. From Budge-Budge onwards upto Haldia chloride content increases and varies from 530 ppm to 3400 ppm, showing a pronounced effect of saline water over freshwater. From Kuchuberia to Digha the chloride content varies from 5600 ppm to 12,800 ppm. The chloride content of the seawater is 19000 ppm. So the low chloride content at Digha can be explained by the fact that the discharge of the Subarnarekha and Contai canal dilutes the seawater. The chloride content of the estuary water is directly related to the mixing phenomena. Therefore, ebb and tide, monsoon and climate mainly govern the chloride content. Abbas (1982) during monsoon 1981, reported the chloride concentration at Calcutta to be 9 ppm. This is clearly due to the dilution of the seawater by

by the increased river-discharge and the high precipitation. Whereas, we observed 18 ppm of chloride concentration at Calcutta (Eden-Garden) during dry season. This may be due to the decreased dilution of the sea-water during the dry season. It has been reported that the heights of high and low waters coming to Diamond Harbour varies from 0.61 m to 5.43 m (Indian Tide Table 1973). Therefore, we get higher chloride concentration from Diamond Harbour downstream.

However, these observations of chloride content variation are based on the surface water sampling, what happens to the chloride concentration with depth can be useful in the understanding of mixing phenomena in the Hooghly estuary.

**Bicarbonate**

The alkalinity of water was determined in terms of $HCO_3^-$. In the upper reaches of the estuary the concentration shows a decreasing trend from 210 ppm to 126 ppm. Subramanian (1979) reported that the average $HCO_3^-$ in the Indian rivers is 90.77 ppm. The high concentration of $HCO_3^-$ in the Ganga and consequently in the Hooghly is due to the fact that it flows through a terrain rich in Kankar-carbonate alluvium. The weathering of these carbonates releases $HCO_3^-$ ions in the water. It has been reported by Garrels and Mackenzie (1971)

that chemical weathering of pure calcite produces $Ca^{2+}$, $Mg^{2+}$ and $HCO_3^-$ in the ratio 1: 1: 4, Besides this, human activities and industrial effluents coming into the river also may be responsible for high $HCO_3^-$ concentration. From Diamond Harbour onwards upto Dighe the $HCO_3^-$ concentration may decrease due to mixing phenomena. The concentration of $HCO_3^-$ in the sea water is 142 ppm; this lower concentration of $HCO_3^-$ dilutes the original riverine $HCO_3^-$ concentration.

Sulphates

The $SO_4^{--}$ concentration varies from 35 ppm to 25 ppm in the upper reaches of the estuary. From Diamond Harbour onwards upto Digha it increases from 100 ppm to 2000 ppm. Chloride and sulphur are not abundant in most igneous and sedimentary rock minerals and so, are not originally derived from rock weathering (Rubey 1951). Therefore, $SO_4^{--}$ does not interact strongly with salinity and biological activity. The high values of $SO_4^{--}$ downstream may come from the sea water (2712 ppm) as a result of mixing. Industrial effluents also may contribute $SO_4^{--}$ in water.

Dissolved Silica

The dissolved silica concentration shows a decrease (7.8 ppm to 0.6 ppm) with increasing salinity (Fig. 5).

Silica is an important nutrient to some marine organisms, e.g., diatoms, radiolaria and sponges, the dissolved silica being removed by such organisms in order to provide skeletal material for extra-cellular structures. Thus, biological processes have a control on the dissolved silica budget of estuaries. There is, however, a paucity of information on the biological 'mechanisms' of silica removal (see, e.g., Spencer 1975), and considerable debate as to the role of non-biological removal of dissolved silica by precipitation during estuarine mixing.

For waters of pH$<$9, which is the usual situation in natural waters, Siever (1971) has demonstrated that the dissolved silica will be present as silicic acid ($H_4SiO_4$). Krauskopf (1956) suggested that during the mixing of river water with sea water in estuaries, the increased electrolyte concentration leads to the formation of polymeric, colloidal form of silicic acid which flocculates and removes dissolved silica. But later studies by Burton et al. (1970) and Siever (1971) have demonstrated that there is no evidence to support the hypothesis that the silicic acid in either river or sea water is in a polymeric form. In addition, when artificial polymers of silicic acid are added to river, sea or estuarine waters there is a rapid depolymerization

to monomers of silicic acid. These observations suggest that the estuarine removal of dissolved silica by the processes of polymerization and flocculation of silicic acid are unlikely (Aston 1980).

While the mechanisms of the possible removal of silica from solution by inorganic processes in estuaries are not understood, several studies have been aimed at determining whether or not removal actually does or does not take place. Early results for several Japanese estuaries (Maeda 1952; Makimoto et al. 1955; Maeda and Takesue 1961) suggested that there is a linear relationship between dissolved silicon concentrations and the chlorinity of the waters. These workers interpreted their findings as evidence for a lack of dissolved silicon removal during estuarine mixing. These early Japanese data are, however, of little real use in the interpretation of conservative/nonconservative behaviour in estuaries, due to the very restricted range of chlorinities examined. Liss (1976) after reviewing various studies concluded that there is adequate evidence for the non-conservative behaviour of silicon in estuaries, with a removal range to 0-30%.

Recently, Sholkovitz (1976) has attempted to use a product approach to the study of the conservative/nonconservative behaviour of dissolved silicic acid during estuarine mixing. He criticized the reactant approach, i.e., that based upon the deviations of the concentrations of dissolved constituents from those predicted by a theoretical dilution curve, on four grounds :

1) The composition of the river water "end-member" of a dilution curve can exhibit large variations and make the line difficult to define.

2) The contribution of more than one source of river water often complicates the mixing assumptions.

3) There is some difficulty in defining the removal products as particulate matter or sediments.

4) The reactant approach will not give an indication of the mechanism of removal.

However, the product approach itself too is not devoid of significant problems. In common with other laboratory experiments which attempt to model geochemical processes in natural waters, there is a basic doubt as to whether the experimental conditions are physically, kinetically and thermodynamically representative of the conditions in the real situation.

Sholkovitz's data on silica removal in estuaries suggests that the extent of the removal is approximately 3-6%.

The extent to which the rapid removal is capable of influencing the dissolved silica budget of estuaries in general is difficult to assess, especially when the environmental factors which control the growth and populations of silica secreting organisms may vary so widely from one estuary to another.

In the present study no attempt has been made to examine the machanism responsible for the silica removal.

Phosphates

The concentration of phosphate shows a slight increase from 0.05 ppm to 0.2 ppm in the upper reaches of the estuary, and afterwards, it becomes nearly constant except Namkhana, where we encounter the $PO_4^{3-}$ concentration 0.3 ppm (Fig. 5). The first detailed study of inorganic phosphate in estuaries was probably that of Steffansson and Richards (1963) who noted that there was a distinct lack of variation of phosphate concentrations in estuarine waters of different salinities taken from the Columbia River Estuary. They proposed that the observed lack of variation of

dissolved phosphate could be attributed to two main causes: (1) the similarity of inorganic phosphate concentrations in the river and sea waters which contribute to the estuary; and (2) the existence of a "buffering" effect which maintains the average phosphate concentration in the estuary at $\sim 37\ \mu gPl^{-1}$.

Phosphate "buffering" by solution-mineral reactions have been cited frequently for fresh water environments (Mortimer 1971; Patrick and Khalid 1974) and recent studies suggest that a similar mechanism can occur in the estuarine environment (Stirling and Wormald 1977). The removal of dissolved phosphate from sea water has been demonstrated to be adsorption onto solid mineral surfaces (Phosphatic and nonphosphatic), and in common with other adsorption processes the extent of removal depends on the phosphate concentration in solution and the mineral surface area available (Chen et al. 1973). The adsorption is at a maximum for the pH range 3-7, so that phosphate removal will be greater in fresh and brackish waters (pH 3-8) than in sea water (pH 8.1). Aston (1980) concluded that the present evidence on the factors controlling phosphate removal in estuaries suggets that removal will be favoured under

low salinity, low pH and high phosphate conditions, i.e., those conditions experienced towards the head of a typical estuary.

If the observed constancy of phosphate distributions is to be accounted for by a so-called "buffering" mechanisms, there must be an opportunity for phosphate contributions to estuarine waters by desorption (Aston 1980). Through biological cycling some of the inorganic phosphorus is converted into dissolved and particulate organic phosphates. The overall rate of biological cycling of phosphorous in estuaries is dependent on environmental factors which can change dramatically in a short time scale compared to that of the open oceans.

In the upper reaches of the Hooghly estuary, the observed increase in $PO_4^{3-}$ concentration may be attributed to the domestic sewage and industrial effluent disposal in the river and the constancy of the lower reaches may be due to the "buffering" mechanism. At Namkhana, we got higher concentrations of $PO_4^{3-}$, this may be due to its different channel characteristics which does not allow rapid flow of water. For most of the time, the water remains

stagnant allowing the decomposition of the organic matter, which eventually contributes the $PO_4^{3-}$ in the water.

Major Elements ($Na^+$, $K^+$, $Ca^{++}$ and $Mg^{++}$)

All the major cations show the increase in their concentration from Chuchura to Digha as shown in table 1.

The outstanding behaviour of potassium in comparison to that of sodium in the hydrosphere has been noted for a long time (Millot 1970). In the course of continental weathering sodium turns out to be much more mobile than potassium and dominates the latter in natural solutions. Potassium is stored up and conserved in a preferential way, on the average in weathering products. The reason for this lies in the behaviour of the $K^+$ ion in water; it does not become hydrated and its apparent volume is three times smaller than that of $Na^+$ ions (Millot 1970). Considering the behaviour of $K^+$ ions in solution, it is seen that they are preferentially adsorped by the fine-grained particles of the sediments. The K/Na ratio is equal to 2.8 for clays, 3.3 for sandstones, and 7.7 for limestones; it is close to 3 for the ensemble of sedimentary rocks (Millot 1970).

Therefore, due to preferential adsorption and incorporation in silicates, potassium is much less abundant in the solution of hydrosphere than sodium. As a matter of fact, both mechanisms function from the beginning of weathering. The downstream increase of both the $Na^+$ and $K^+$ in the Hooghly may be due to mixing phenomena. The low concentration of $K^+$ in comparison to that of $Na^+$ in water may be due to its uptake by clay minerals, especially Illites.

Calcium and Magnesium are considered to be two ions with similar behaviour, and this is true in many phenomena of the hydrosphere. In the Hooghly estuary both the $Ca^{++}$ and $Mg^{++}$ show a downstream increase in their concentration. $Ca^{++}$ varies from 35 ppm to 398 ppm where as the $Mg^{++}$ varies from 15 ppm to 1200 ppm. The $Ca^{++}/Mg^{++}$ ratio in the fresh water region is 5.7, in the brackish water zone it is 1.44 and in saline region it is 0.32. This variation shows that the increase of $Mg^{++}$ ion in the water is much marked than that of $Ca^{++}$ ion. This may be due to the fact that during the reorganization of clays by transformation from open, interstratified, or degraded minerals, as well as by neoformation of

magnesium clay minerals, magnesium is consumed in large quantities in the fresh water zone of the Hooghly estuary and this consumption of $Mg^{++}$ may be decreasing downstream. The source of both the $Ca^{++}$ and $Mg^{++}$ is in the carbonate sediments of the river basin and its catchment area. The other reason of the increase of $Mg^{++}$ concentration is the mixing phenomena. The seawater contains 1294 ppm $Mg^{++}$ and only 142 ppm of $Ca^{++}$ (Cox and Culkin 1967). Besides this, the carbonate-precipitation, especially of Calcite may also be one of the reasons of $Ca^{++}$/ $Mg^{++}$ variation downstream.

Total Suspension Material (TSM)

In general the TSM shows an increase from 55 ppm to 1430 ppm downstream (Fig. 5) with some variation in between.

Rao (1979) pointed out that silt carried by the Ganges often exceeds 2000 ppm. Many factors affect the distribution of particulate matter in estuaries and make quantitative estimates of the net suspension transport difficult if not impossible (D'Anglejan and Smith 1973). The controlling factors are: distance and variety of sources, stream discharge, basin geology, tidal and non-tidal circulation, bathymetry, water

stability, flocculation, size and specific gravity and wind. The resulting complex tridimensional distribution changes rapidly, and to a large extent randomly, with time, and cannot be accounted for simply in terms of diffusion and dispersion. For each individual estuary, continuous observations must be made along its length and width to record time changes in the horizontal and vertical gradients of the major properties (D'Anglejan and Smith 1973). Studies of this kind have been made in various parts of the world, particularly in the Wadden Sea (Postma 1954), New England Estuary (Anderson 1970; Chesapeake Bay (Schubel 1968, 1969) and the Amazon river (Gibbs 1967), the Ganges basin (Subramanian 1979; Abbas 1982).

The TSM and the water chemistry are closely related. The natural waters having lower intermediate level of electrolyte-concentration with high sodium concentration, may bring about the dispersion of clays. The water carrying clay dispersion in suspension may flocculate if the chemical environment changes. Dispersion is likely to occur if soils in the drainage basin have high percentage of exchangeable sodium (ESP), the chemical balance between dispersion and flocculation in stream water, is determined

amongst other things, by the thickness of the diffuse double layer around the particles, which reflects both the chemical composition of this layer and the stream water chemistry, i.e., its electrolyte content. At high electrolyte concentrations, particle agglomeration generally occurs at maximum rate, being determined almost solely by diffusion (rapid coagulation). At intermediate electrolyte concentrations, the coagulation process is retarded to such an extent by the appreciable high range repulsion that for all practical purposes, the suspension is stable under these conditions (Van Olephen 1977).

In the upper reaches of the Hooghly estuary we find lower concentrations of the TSM, except Bauria (950 ppm) and Budge-Budge (1490 ppm), because of low river discharge in dry season and the control of river water volume by the Farrakka Dam. The high TSM encountered at Bauria and Budge-Budge may be due to the confluence of Kunti river below Howrah, and the tidal influence. The day samples were collected from these two locations, high wind was blowing, this must have contributed in the resuspension of the clay particles resulting in the consequent increase in TSM. At Haldia, again, the

Haldia river joins, which may be the cause of high TSM over that point, At other points, except Kakdwip Bakkhali, the high TSM may be due to tidal phenomena. The samples from both the places Kakdwip and Namkhan were collected early in the morning, when there was no breeze and no tide at all. The water was cool and calm. This may be the cause of low TSM over those points.

Assessment of Water Quality

From Chuchura to Budge-Budge, bicarbonates are nearly 50% of the total anions present. But from Diamond harbour onwards bicarbonates are replaced by the chloride ions, constituting more than 50% of the total anions. Calcium ions, from Chuchura to Budge-Budge dominates and is nearly 50% of the total cations. So, we may say that upto Budge-Budge the estuary water is of calcium bicarbonate group. From Diamond Harbour upto Digha, though the concentration of $Ca^{++}$ ions increases, but it is outnumbered by the $Na^{+}$ ions, which exceed the 50% of the total cations.

Thus, we may say that the Hooghly estuary water from Chuchura to Digha is alkaline, but it is more alkaline only upto Diamond Harbour beyond it the alkalinity slightly decreases.

The U.S. Public Health Service (1946) has given the following specification for the Drinking Water:

| | |
|---|---|
| T.D.S. (Good Quality) | - 500 ppm |
| Where no better water is available | - 1000 ppm |
| Chloride | - 250 ppm |
| Sulphate | - 250 ppm |
| Magnesium | - 125 ppm |
| Iron and Manganese | - 0.3 ppm |

Taking this specification into account, and ignoring the pollutional aspect, we may say that the estuary water only upto Budge-Budge is suitable for the domestic use. The Indian Standard IS 3025-1964 lays down the tolerance limits for inland surface waters for irrigation : pH 5.5 to 9; electrical conductence at 25°C 3000 X $10^{-6}$MHO; TDS (inorganic) 2,100 ppm; sulphate 1000 ppm; chloride 600 ppm. This specification is fulfilled by the Hooghly upto Kukrahati and therefore, water can be used for irrigation in this region.

The idea that these three major mechanisms - atmospheric precipitation, rock dominance, and the evaporation-crystallization process - control world water chemistry is borne out by a consideration of

the major anions of the world's water; chloride and bicarbonate and cations sodium and calcium (Gibbs 1970). A presentation similar to that is given in figure 6) for cations and in figure 8 for anions. For the purpose of comparison and clarity the cations and anions of the sea water and river water mixed in various proportions were calculated and plotted with the observed plot.

In figure 6), we observe, when the sea water is being diluted by the river water upto 90%, a vertical decrease in the Na/Na+Ca ratio with the decreasing TDS. But there is a steep deviation in the Na/Na+Ca ratio for the mixture of 10% sea water plus 90% river water to 100% river water. The observed plot has the same trend upto 6000 ppm TDS, but it is slightly shifted to the left indicating that the ratio of Na/Na+Ca is slightly lesser than what should, actually, be theoretically. This discrepancy can be explained by taking into account the relief, vegetation and composition of material in the basin. Therefore, from Haldia to Digha, we find that the Hooghly water is being diluted by the Bay of Bengal water. And even at Digha we do not get pure sea water, but a mixture of nearly 70% sea water and 30% river water. In the upstream from Haldia to Chuchura, we find that the

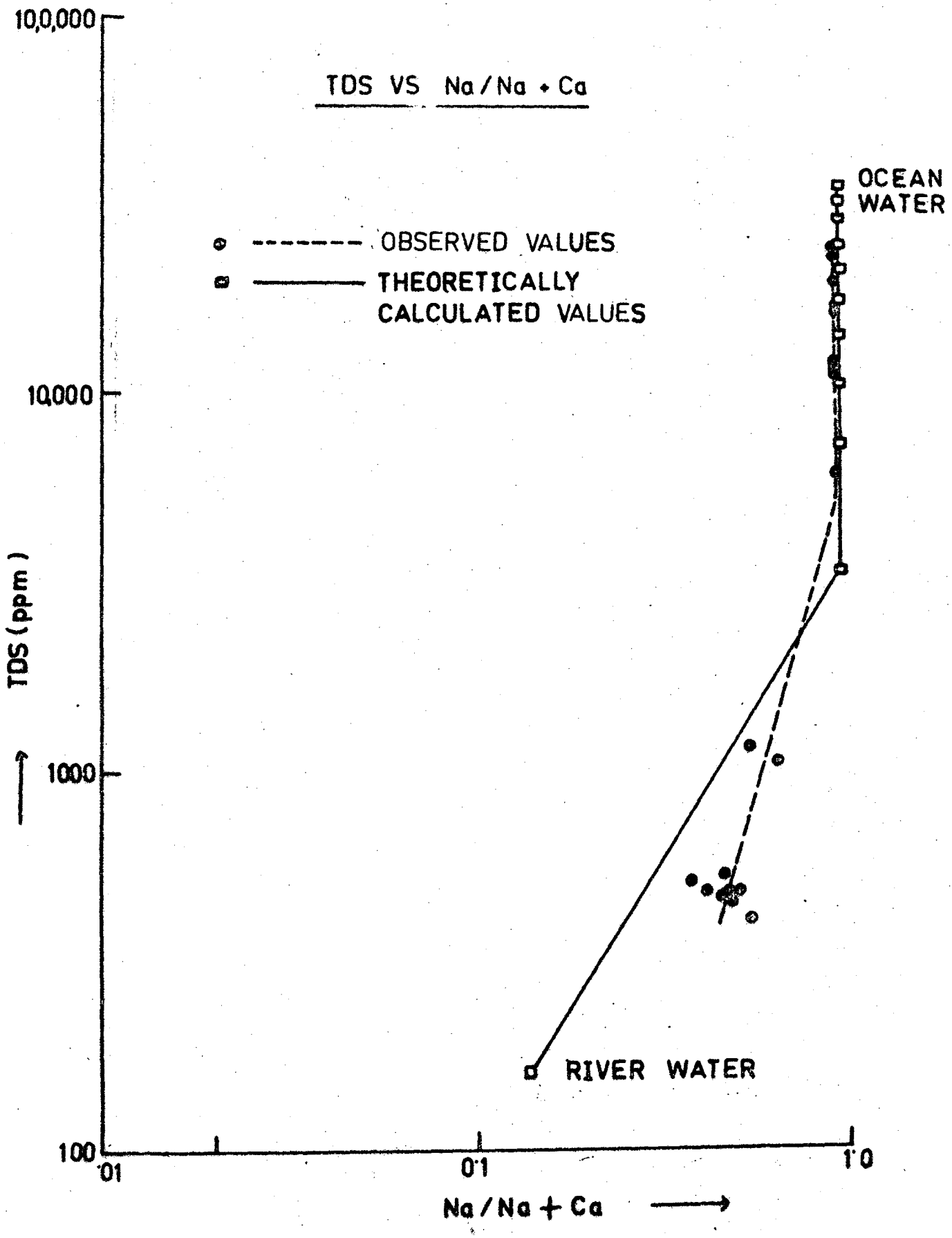


Fig. 6. Comparison of theoretically computed Na/Na+Ca & TDS with obsed values

Na/Na+Ca ratio is higher than the theoretically calculated values, because as evident from the graph itself, that even at Chuchura, the Hooghly river is not a river with freshwater only, but a very low percentage of sea water used to reach there and causes the increase in the $Na^{+}$ and $Ca^{++}$ content of the water. Besides this, Kankar carbonate rich alluvium also provides $Ca^{++}$ to the water.

In figure 7, variation of anions are shown, Even in this case, a theoretically computed ratio of the said ions are plotted for the purpose of the comparison. As is evident from this graph, both the TDS and the $Cl/Cl+HCO_3$ ratio from Chuchura to Budge-Budge is greater than that of the typical river water. This is because of the mixing phenomena. Saline water has high chloride content. Diamond Harbour and Kukrahati due to its brackish nature are above the line. From Haldia to Digha both the $Cl/Cl+HCO_3$ ratio and TDS are lower than the theoretically calculated value. This shows that the oceanic water coming to these places are not pure oceanic, at the same time this indicates that the estuary extends to a larger distance in the Bay of Bengal.

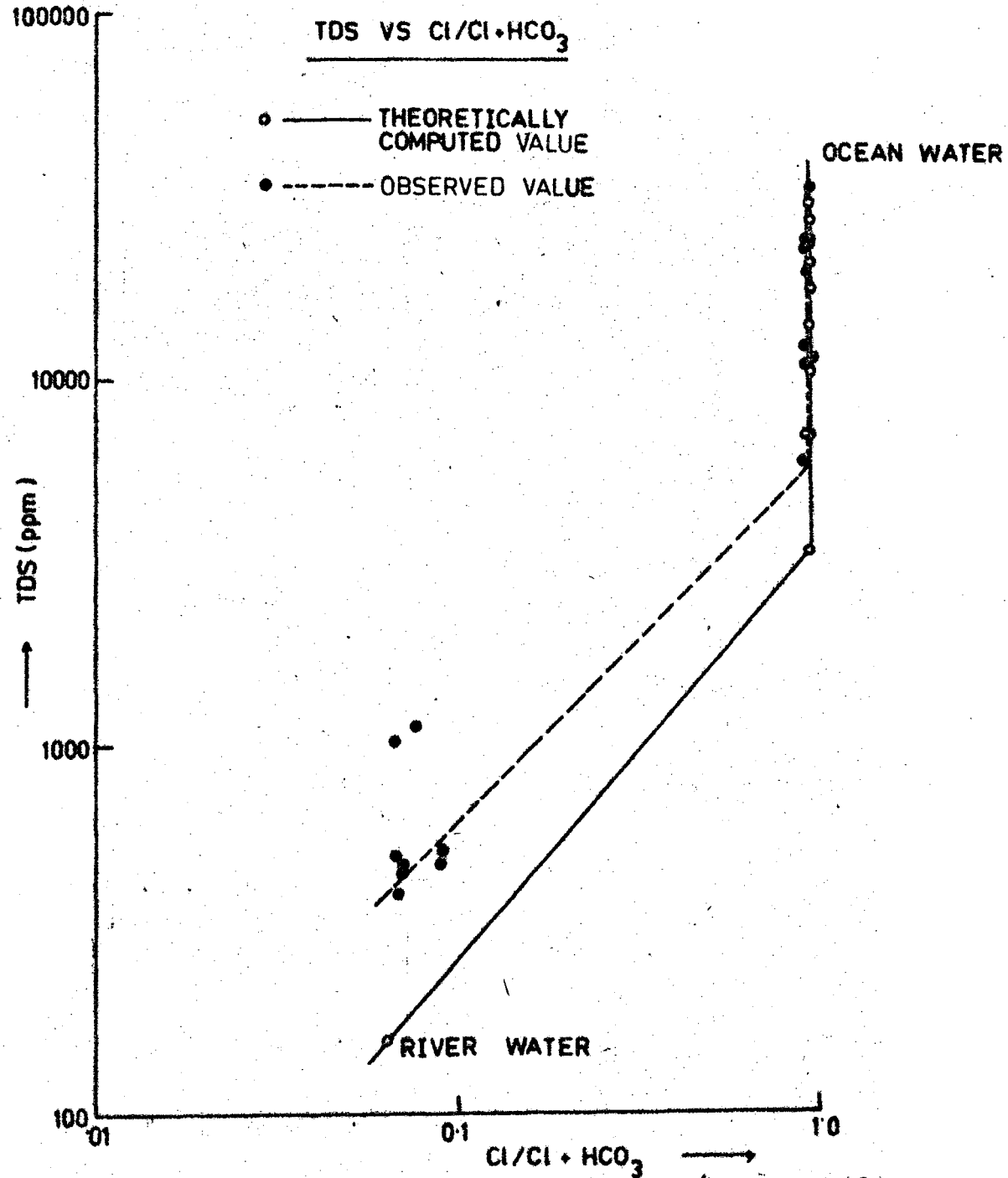


Fig. 7 Comparison of theoretically computted $Cl/Cl+HCO_3$ & TDS with observed values

Thus, we see that the water quality of the Hooghly estuary is not merely governed by atmospheric precipitation, rock dominance and the evaporation-crystallization process but also by second order factors such as relief, vegetation etc.

Bed Sediments

Sediments are the product of transport and environment of deposition and also of provenance. Consequently a short survey of the mineralogical compositions of the bed sediments was carried out. The mineralogical composition of the sediments in a depositional basin will be mainly determined by the nature of the rocks in the source areas. However, the composition is also a function of weathering of unstable minerals (in the source areas, during transport or after deposition) and of selective sorting during transport (according to size or density). Both these factors can modify the composition between the source rocks and depositional site. Fine grained sediments (clays and silts) make up much of the fill of ocean basins and the modern deposits of coastal and shelf environments.

It is now a well established fact that there exists a close relationship between grain size patterns

and depositional environment (Folk and Ward 1957; Visher 1965, 1969; Klovan 1966; Allen et al. 1971). Therefore, the grain size analysis of the bed sediments were also done.

The sediments of the Hooghly estuary have been mainly derived from the Ganges-Brahmaputra system. The relative sediment load of the Ganges delta is very high as compared to the Mississippi or Mekong delta. The annual average discharge at the mouth of the delta is 493400 $m^3$ and the drainage area is 1050 X $10^3$ $Km^2$ (Rao 1979). A number of other rivers such as Kunti, Damodar, Rupnarayan, Haldia and also Subernrekha contribute the sediments. The Ganges rises in the Himalayas and drains various types of metamorphites, Paleo-Mesozoic and Tertiary sediments and Quaternary rocks. These are overlain by alluvial deposits, stream deposits, deltaic and tidal deposits.

Mineralogy

Mineralogy of the bed sediments was determined by X-ray diffractography (X.R.D.) data. The percentage abundance of the minerals are given in Table 2.

TABLE 2: MINERALOGY OF THE BED SEDIMENTS OF THE HOOGHLY ESTUARY

| Locations Arranged in Increasing Chlorinity (ppm) Written in Bracket | Percentage of Various Minerals | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Dolomite | Calcite | Feldspar | Quartz | Chlorite | Kaolinite | Amphibole | Illite | MLC* | Montmorillonite |
| Eden Garden (18) | 30 | 1 | x | 1 | x | 64 | x | x | 2 | 2 |
| Bauria (18) | 19 | x | 6 | 20 | 3 | 20 | x | 32 | x | x |
| Budge-Budge (18) | <1 | 5 | 10 | 59 | 1 | 4 | x | 20 | x | x |
| Dakshineswar (22) | 5 | 5 | 2 | 58 | 2 | 11 | x | 17 | x | x |
| Howrah (24) | 68 | x | 5 | x | x | 12 | 15 | x | x | x |
| Kukrahati (530) | 11 | 26 | 5 | 51 | x | x | x | 7 | x | x |
| Diamond Harbour (680) | 2 | 10 | 10 | 50 | 3 | 11 | x | 14 | x | x |

MLC* : Mixed layer clay

(contd...

TABLE 2: MINERALOGY OF THE BED SEDIMENTS OF THE HOOGHLY ESTUARY (contd..)

| Locations Arranged in Increasing Chlorinity (ppm) written in Bracket | Percentage of Various Minerals | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Dolo-mite | Cal-cite | Felds-par | Quartz | Chlo-rite | Kaoli-nite | Amphi-bole | Illite | MLC* | Montmori-llonite |
| Haldia (3400) | 3 | 6 | 9 | 43 | 2 | 12 | x | 24 | 1 | 1 |
| Kuchuberia (5600) | 1 | <1 | 24 | 40 | 5 | 10 | x | 19 | x | 1 |
| Kakdwip (6100) | 3 | 2 | 8 | 29 | x | 7 | x | 51 | x | x |
| Namkhana (8391) | 2 | <1 | 35 | 38 | 3 | 3 | <1 | 17 | <1 | <1 |
| Ganga Sagar (9800) | x | x | 37 | 11 | x | x | x | 52 | x | x |
| Bakkhali (12600) | x | x | 19 | 61 | <1 | 3 | x | 16 | x | x |
| Digha (12800) | 5 | x | 83 | 9 | x | 1 | 1 | x | x | 1 |

*MLC: MIXED LAYER CLAY.

Clay-Minerals

The most abundant clay mineral is Kaolinite, followed by illite and chlorite. Montmorillonite and the Mixed Layer Clays (MLC) are present only in traces. Figure (8) shows the variation of clay minerals in the estuary. Kaolinite is more abundant in the fresh water environment ranging from 4 - 64%, where as its abundance decreases to 1-12% in the saline environment. Quite contrary to it illite shows an increased abundance in the saline environment ranging from 7-52%, whereas, its presence in fresh water region ranges from 17-20%. Chlorite remains less conspicuous in the fresh water zone ranging from 1-3% whereas, in saline environment it goes as high as 5%.

Kaolinite, illite and chlorite are the chief constituent of the suspended particulates of the Ganges (Subramanian 1980, Abbas 1982). Despite the relatively high illite throughout the Ganges Province, Venkatarathnam and Biscaye (1973) found an even higher abundance of this mineral in the distal lobes on either side of the Ninty East Ridge than in the proximal area in the eastern Bay of Bengal. Siddiqui (1967) reported illite as the predominant clay

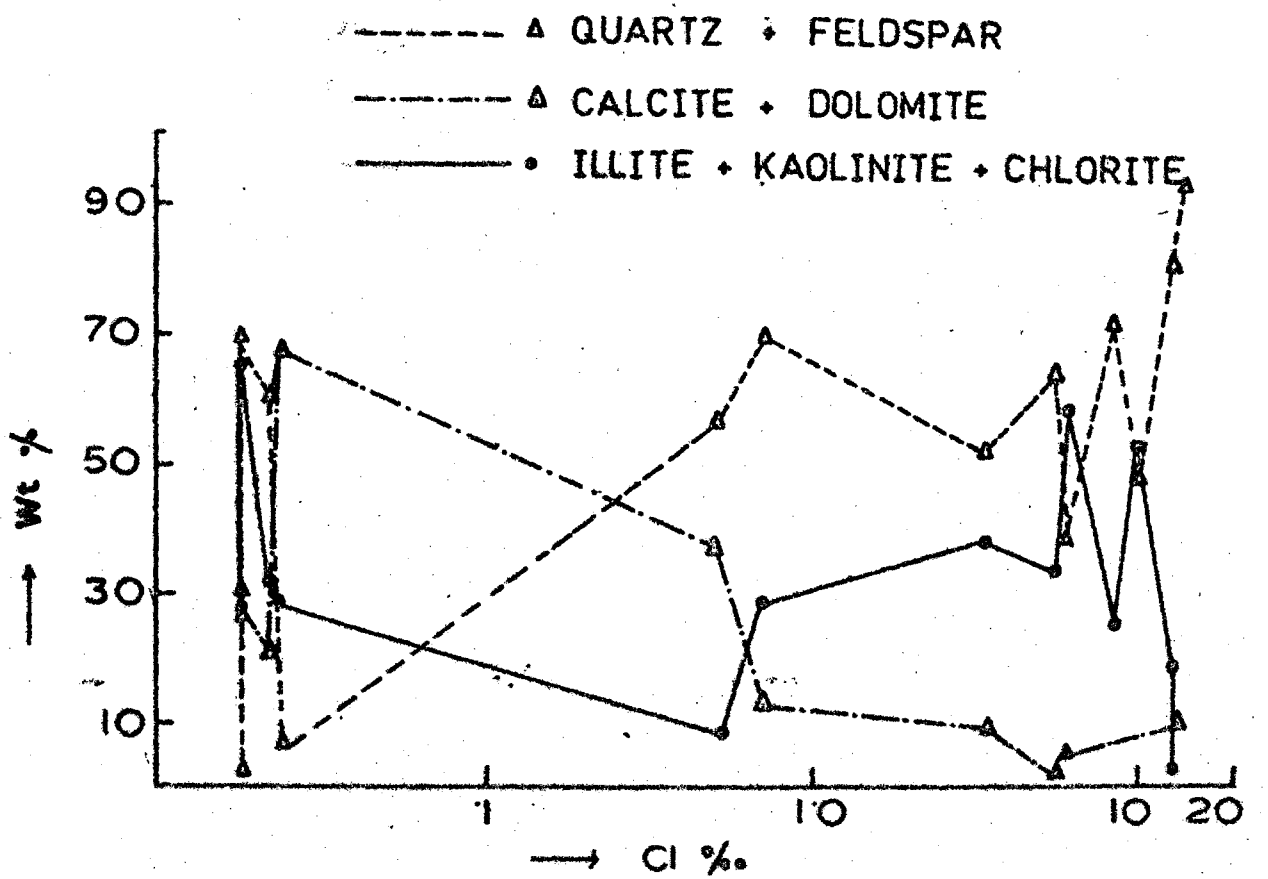


Fig.8. Variation of minerals with chlorinity.

mineral in the Bay of Bengal, together with Kaolinite and montmorillonite. Goldberg and Griffin (1970) recorded abundant illite, chlorite, montmorillonite in the eastern part of the Bay due to the influence of the Ganges-Brahmaputra. Subramanian (1980) also reported the presence of montmorillonite in the TSM of the Ganges water. Shanmugam (1964) suggested that the top layer of the Hooghly River contains muscovite, kaolinite and quartz and the bottom layer contains palygorskite, muscovite, quartz, kaolinite and illite. A high concentration of montmorillonite has been reported by Subba Rao (1964) in the east-coast shelf sediments derived from the Deccan traps. Mallik (1976) reported that kaolinite and illite are the principal clay minerals in the sediments of the western part of the Bay of Bengal.

The source of the clay minerals found in the sediments may be (a) Detrital inheritance, (b) transformations and (c) Neoformations. It has been reported that kaolinite is in equilibrium with Ganges water (Handa 1972; Abbas 1982). So, some of the kaolinite in the Hooghly estuary may be inherited. At the same time, some of it may be the weathering product of feldspar. Millot (1970) pointed out that

What does this mean

the kaolinite is stable in the hydrosphere, in soils and in sediments, and it is the most typical and the most resistant inherited clay mineral. Further, he reported that in more moderately leached environments silica is present in solutions and alumina is associated with it there to give rise to kaolinite ($SiO_2/Al_2O_3 = 2$). Millot (1970) concluded that the presence of bivalent cations in an environment favours the formation of micaceous minerals and blocks the genesis of kaolinite. This may be the possible reason for the lesser abundance of the kaolinite in the lower reaches of the Hooghly. However, this view supports the neoformation of kaolinite. Another possible reason of the down stream variation may be the differential settlings of the individual clay minerals. Whitehouse, Jeffrey and Debrecht (1960) determined the settling velocity of illite, kaolinite and montmotillonite in a calm sea water at 18‰ salinity and 26°C to be 15.8, 11.8 and 1.3 m/day respectively. Chlorite settles slightly faster than kaolinite and vermiculite slightly faster than illite. The role of organic matter was also studied; hydrocarbons increase the settling velocity of montmorillonite, but protein decreases it. Humic matter and protein

stabilize kaolinite considerably. Illite is not affected. Powers (1959) pointed out that the clays are in a flocculated state immediately after their entry into the estuary and long before their arrival in the sea. But Riviere and Vernhet (1951) studied the speed of flocculation of illite, montmorillonite and kaolinite in the presence of trace amounts of humic matter, kaolinite acquired a great resistance to the flocculation provoked by bivalent ions and notably by those of sea water. Therefore, kaolinite may settle first in comparison to illite, chlorite and montmorillonite. Montmorillonite may be flowed away into the ocean. This may be one of the possibilities due to which we do get montmorillonite in traces in the bed sediments, inspite of their presence in TSM.

Illite and chlorite are common detrital minerals inherited by numerous soils and sediments. They are stable during weathering of an overridingly physical character, in poorly drained soils of modest chemical activity, in sediments deposited in alkaline water (Millot 1970). He further pointed out that cations enter into the neoformations of three-layer

minerals of micaceous type, but this does not occur for kaolinite, which is uniquely aluminous. Potassium is necessary for the formation of illite. Iron and Magnesium are necessary for the elaboration of chlorite, chamosite and glauconites. As is evident from the water chemistry that there is sufficient amount of $K^+$ and $Mg^{++}$ to allow the formation of illite and chlorite by halimyrolitic reactions in saline region of the Hooghly estuary. This may be the cause of increased abundance of chlorite and illite in the lower stretches of the Hooghly. However, some amount of illite and chlorite are also of the inherited nature, because they are reported in the TSM throughout the Ganges basin by Subramanian (1980) and Abbas (1982).

Griffin and Ingram (1955) studied the clays brought into the estuary of Neuse river in North Carolina. These are kaolinite, chlorite, illites and montmorillonite, as well as amorphous or weakly crystalline material that can amount to 50%. They pointed out that down the estuary, chlorite increases relative to kaolinite and illite relative to kaolinite and chlorite. Millot (1970) pointed out that this variation may be due to transformation of neoformation of minerals. Nelson (1958) studied the clay minerals

of the bed sediments of Rappahannock River estuary and identified Kaolinite, illite, vermiculites, mountmorillonite, chlorite, feldspar and Quartz. He observed that illite becomes better and better crystallized and more abundant down the estuary. Montmorillonite decreases and chlorite appears.

In the Hooghly estuary also we find that the kaolinite decreases downstream, illite becomes abundant and chlorite shows an increase. Therefore, it is tempting to explain these changes by mineralogical evolution of the clay minerals under the influence of the transition from freshwater to marine water. But there is a risk of being deceived by supplemental, laterally supplied sediment, or by the conditions of transportation and dispersal of the sediments within the estuary. The lateral trends in the clay mineralogy of bottom sediments may be explained by three mechanisms (a) chemical alteration, (b) differential flocculation and (c) size segregations. It is likely that in the Hooghly, chemical alteration of clay minerals plays a minor role. The role of flocculation may not be of much importance because the turbulence and the organic and/or metallic coatings on the particles may interfere in this process making it less effective. But the dominant

mechanism responsible for the laterally changing clay minerals of the bottom sediments may be the physical sorting of sediments by size under the influence of the longshore currents in the downstream reaches. This view is supported by decreasing abundance of clay minerals in the downstream, but their concentration, especially that of illite, is reported high in the Bay of Bengal sediments. However, it requires a detailed study before making any exclusive comment.

Detritals (Quartz and Feldspar)

Quartz and feldspar are present in the bed sediments throughout the estuary. But as is evident from the Fig. (8), that, quartz decreases downstream, whereas feldspar shows an increase. Fig. (9) shows that Q/F ratio decreases downstream.

Both the quartz and feldspar are the product of the mechanical breakdown of igneous, metamorphic as well as sedimentary rocks of the catchment area of the river. Due to attrition they become smaller in dimension. The solubility of silica is independent of the natural range of pH reported for natural water. Feldspar is susceptible of the chemical weathering and gives rise to clay minerals. Since the percentage of clay minerals

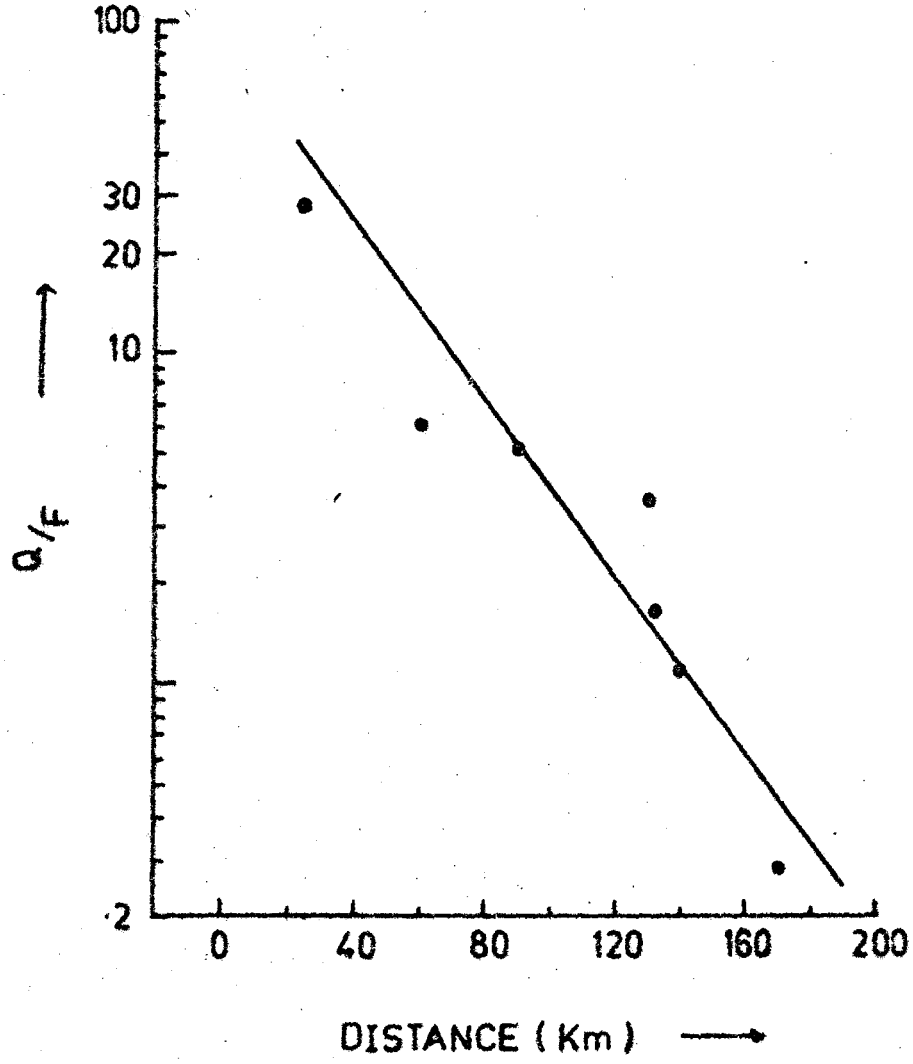


Fig. 9.. Variation of Q/F ratio along distance.

decreases down stream (Fig. 10), it may be inferred that the chemical alteration of the feldspar too decreases, with a consequent increase in its abundance. Besides this, in the lower reaches of the estuary, Damodar, Rupnarayan, Haldia and Subarnrekha also contribute their sediments characteristic of their basin, they also may be responsible for the consequent increase of feldspar and decrease of clay minerals. The sorting mechanism may also be responsible for the redistribution of the minerals. The longshore currents, tides etc. may remove the finer and lighter particles and redeposit them elsewhere, leaving behind the coarser and heavier minerals particles.

Carbonates (Calcite and Dolomite)

Both the calcite and dolomite show the downstream decrease in their abundance (Fig. 8). In the freshwater region of the estuary, dolomite is more conspicuous than calcite. On the basis of the study of TSM mineralogy, Abbas (1982) reported that Dolomite is stable in the Ganges water. In most natural water, the dolomite does not precipitate, except in some hot springs, salt-lakes and in muds of salt lagoons undergoing strong solar evaporation. It is believed that

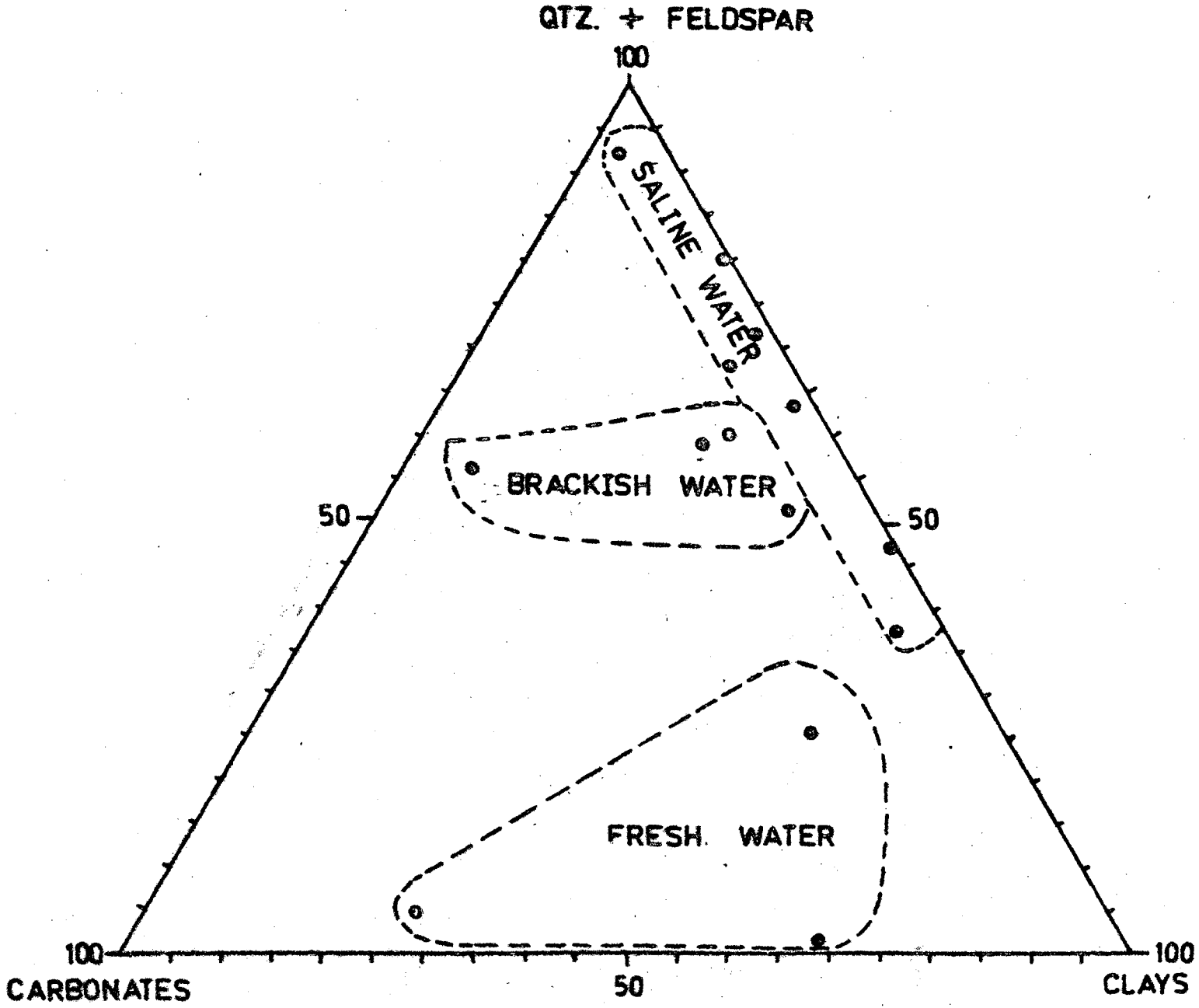


Fig. 10. Triangular diagram showing the composition of the bed sediments.

dolomites are formed by the conversion of calcium carbonate after deposition.

Abbas (1982) reported that in the Ganges TSM dolomite ranges from 1-7% and calcite ranges from 1-35%. On comparing these values with those of the bed sediments of the Hooghly estuary a marked difference is noticed (see Table 2). Obviously, the dolomites may not be a primary precipitate but, the clastic in nature. It has been reported that calcite may precipitate at pH 7.8 or above (Krambein and Garrels 1952). The calcite content of the bed sediment may be a chemical precipitate. Seetaramswamy (1968) reported that the average calcium carbonate content of the off-Krishna Delta sample is 8.08% and that off-Nizampatam Bay is 14%. He reported that the depth is not the controlling factor of calcium carbonate in the top and bottom portions of the core in the area off-Krishna delta. In the samples off Nizampatam Bay, the percentage of calcium carbonate is higher in the bottom than the top portions. Organisms also contribute the carbonates. But such studies were not made in this text.

Based on the percentage abundance of clays, carbonates and detritals, a tringular diagram (Fig. 10) has been made to understand the overall composition

of the bed sediments and to observe its variation. Since the TSM mineralogy was not done, so it is not possible to provide the correlation of the mineralogy with that of bed sediments in the Hooghly estuary.

Grain Size Analysis

The bed sediments consist of medium sand to coarse silt (1.5 - 4.5 ϕ). The per cent population of grain size is given in Table 3. And various graphic measures are listed in the appendix.

It has long been recognised that grain size distributions should reflect the hydraulic environment in which the grains were transported and deposited (Lambaise 1980). Several approaches have been used to interpret depositional environment from grain size distribution such as plotting skewness versus sorting (Friedman 1961), comparing the coarsest fraction to the median size (Passage 1964) and analysing cumulative curve shape (Visher 1969). Recent works have examined the relationships between grain size distributions and hydraulics (Middleton 1976; Sagoe and Visher 1977). According to this approach the effects of the transporting fluid on sediment grains provide a basis for interpreting hydraulic conditions from grain size distributions.

TABLE 3: SIZE DISTRIBUTION OF THE BED SEDIMENTS IN THE HOOGHLY ESTUARY

| Locations Arranged in increasing salinity Their distance from Chuchura is given in K.M. in Brackets | Per cent population in grain size PHI ($\phi$) interval | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | >4.5 | 4.5-4 | 4-3.5 | 3.5-3 | 3-2.5 | 2.5-2 | 2-1.5 | <1.5 |
| Eaden Garden (37) | 10 | 47 | 16 | 16 | 8 | 1 | x | 1 |
| Bauria (55) | 18 | 69 | 5 | 4 | 3.4 | <1 | x | x |
| Budge-Budge (60) | 6 | 31 | 12 | 32 | 14 | 3 | 1 | 1 |
| Dakshineswar (26) | 6 | 23 | 16 | 28 | 26 | 1 | <1 | <1 |
| Howrah (36) | 13 | 46 | 7 | 24 | 8 | 2 | <1 | x |
| Kukrahati (91) | 7 | 27 | 19 | 29 | 14 | 4 | <1 | x |
| Diamond Harbour (90) | 7.4 | 35 | 16 | 27 | 12 | 2 | <1 | x |
| Haldia (120) | 2 | 6 | <1 | 13.4 | 66 | 9 | 3 | x |

(contd...

TABLE 3: SIZE DISTRIBUTION OF THE BED SEDIMENTS IN THE HOOGHLY ESTUARY (Contd..)

| Location Arranged in increasing salinity Their distance from Chuchura is given in K.M. in Brackets | Per cent population in grain size PHI (ϕ) interval | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | >4.5 | 4.5-4 | 4-3.5 | 3.5-3 | 3-2.5 | 2.5-2 | 2-1.5 | <1.5 |
| Kuchuberia (132) | 2 | 9 | 8 | 33 | 42 | 5 | <1 | <1 |
| Kakdwip (230) | 12 | 63 | 8 | 12 | 4.4 | <1 | x | x |
| Namkhana (140) | 2 | 8 | 11 | 35 | 42 | 1 | <1 | <1 |
| Ganga Sagar (165) | <1 | 2 | 3 | 12 | 82 | <1 | <1 | <1 |
| Bakkhali (150) | <1 | 4 | 5 | 20 | 71 | <1 | x | x |
| Digha (200) | <1 | 5 | 9 | 43 | 37 | 2 | <1 | 3.4 |

The aerial distribution of the mean grain size is depicted in Fig. 11 & 12. Fresh water sediments are dominated by the finer sediments (mean size 3 - 4 ø), where as the sediments at the mouth of estuary are dominated by coarser sediments (mean size 3 - 2.5 ø), with a zone of transition in between depicted as brackish water sediments in Fig. 11. Thus, the sediments become coarser towards the estuary mouth. A reduction in the size of bed material with distance downstream is a feature common to many alluvial streams (Knighton 1980). In estuary regions these relations may not hold good. This may be due to hydraulic and channel variation in the estuary. The tides may remove the finer sediments and leave behind the coarser particles.

What are these processes?

Sorting also varies with position in estuary. Sediments at the estuary mouth are poorly sorted than those near the head (Figs. 11 and 13a). The discharge of sediments and water by the tributaries downstream also complicate the sorting mechanism. The mineralogy of the bed sediments are related to the grain size. Gibbs (1977) pointed out that the dominant mechanism responsible for the laterally changing composition of the clay minerals of the bottom sediments in the

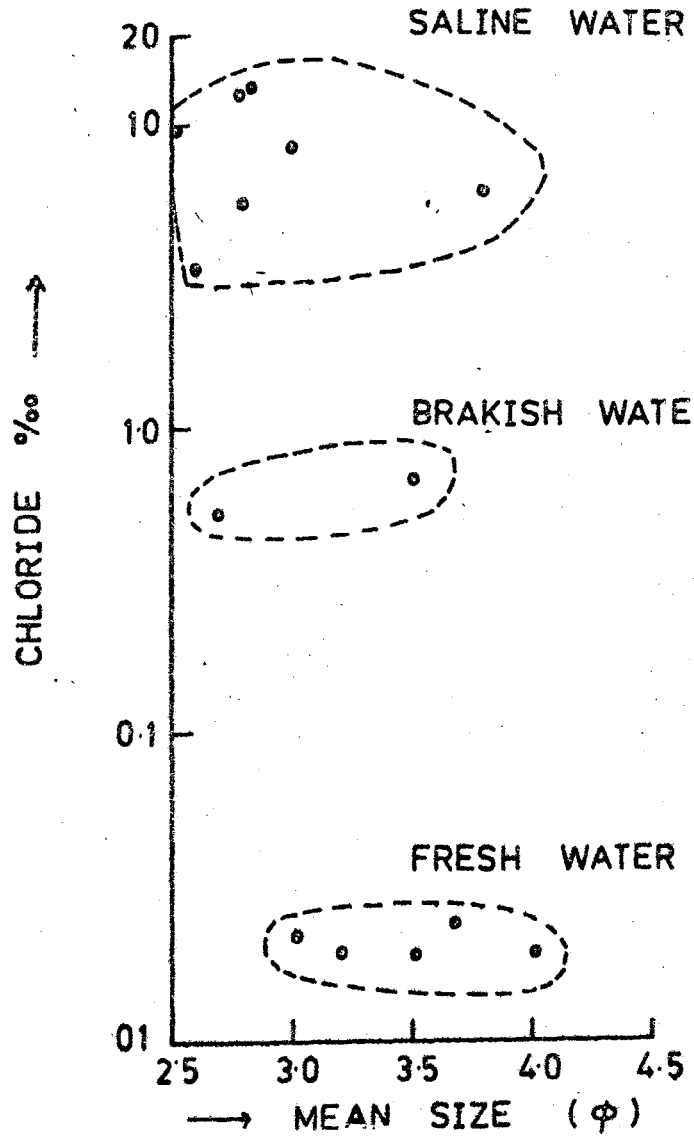


Fig.11 SCATTER PLOT, CHLORIDE CONTENT OF ESTUARY WATER VS MEAN SIZE OF THE GRAINS OF BED SEDIMENTS

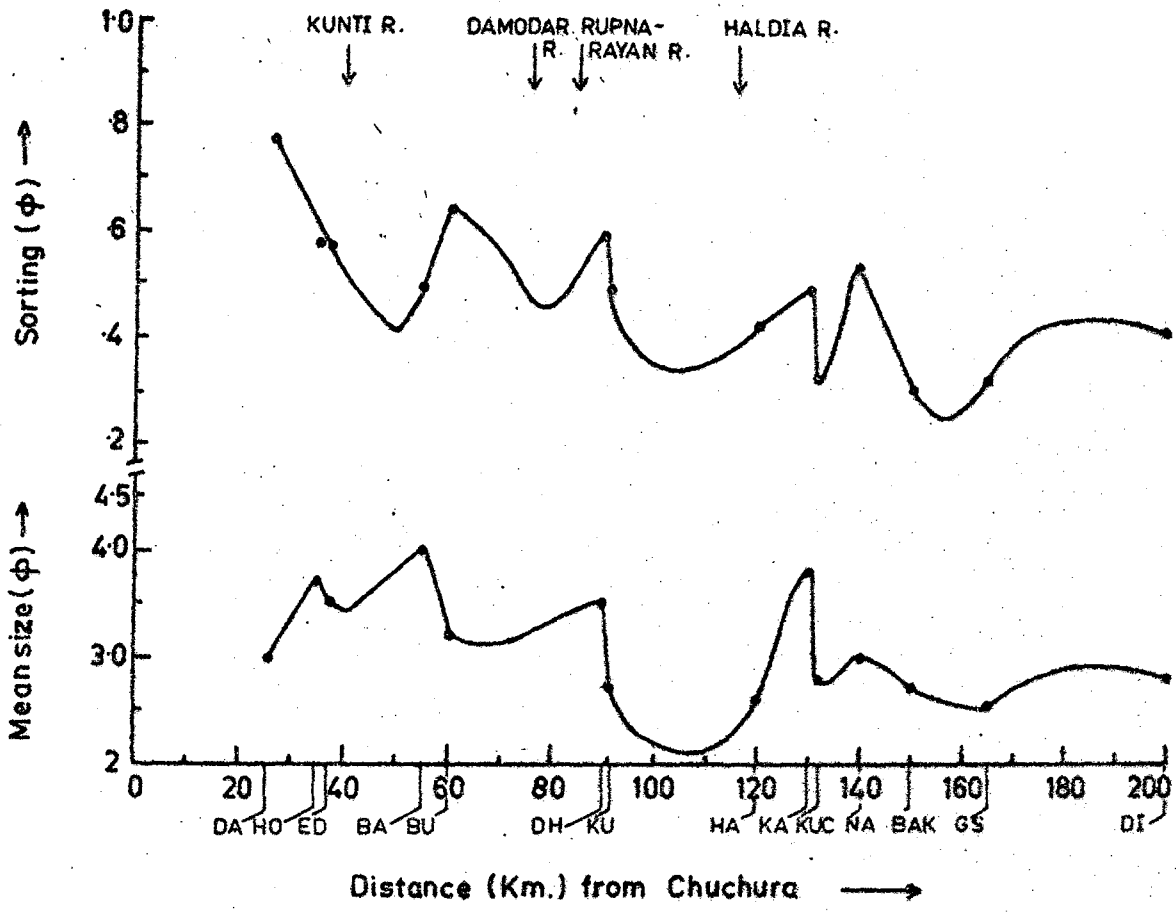


Fig.12. Variation of mean size & sorting along distance.

DA. = Dakshineswar. HO. = Howrah. ED. = Eden Garden. BA. = Bauria. BU. = Budge-Budge.
DH. = Diamond Harbour. KU. = Kukrahati. HA. = Haldia. KA. = Kakdwip. KUC. = Kuchuberia.
NA. = Namkhana. BAK. = Bakkhali. GS. = Ganga Sagar. DI. = Digha.

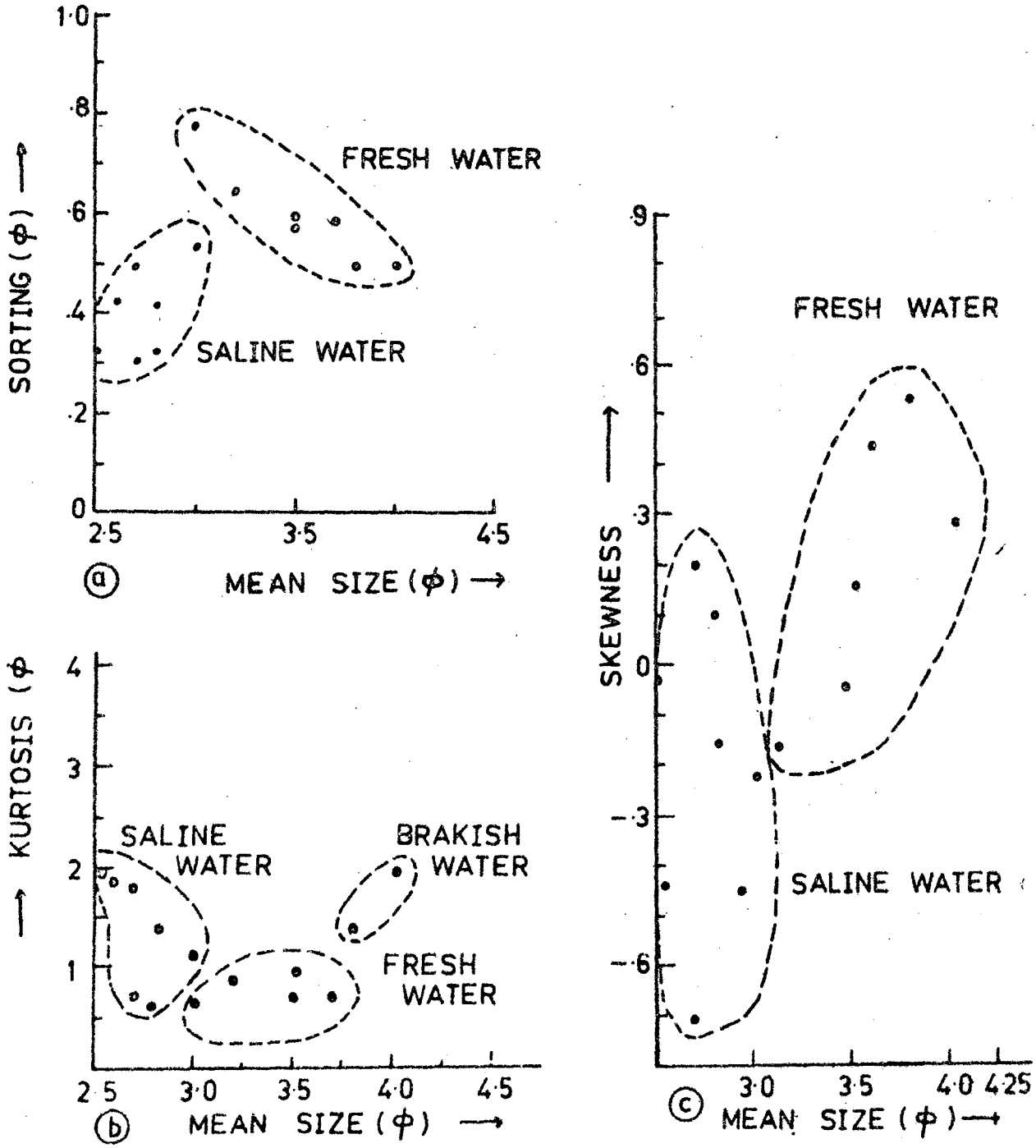


Fig. 13. ⓐ Relationship of sorting with meansize

ⓑ Relationship of kurtosis with meansize

ⓒ Relationship of skewness with meansize

physical sorting of sediments by size. Since the percentage of the clay minerals decreases downstream, the bed sediments consequently become coarser. Sediments at the estuary mouth are negatively skewed because of the presence of a large coarse grain population and positively skewed sediments dominate the estuary head because the coarse population is absent (Fig. 13c and 14).

circular argument

The measure of Kurtosis shows the peakedness of distribution. The fresh water sediments have kurtosis less than one, signifying the flattened curve, whereas the saline sediments have kurtosis greater than one showing peaked curve (Fig. 13b). Again the cause of this flattened and peaked distribution of the sediments may be the changing hydraulic environment.

What is the argument be more specific

Numerous authors have proposed that cumulative frequency curves actually are composed of two or more log-normally distributed grain populations and that the shape of a cumulative curve is a function of the relative proportions of these populations (Lambaise 1980). It has been also observed that each grain population is related to a different sediment-transport mechanism (Visher 1969). Recent work provides a theoretical basis for hydraulic control of cumulative curve characteristic (Safoe and Visher 1977).

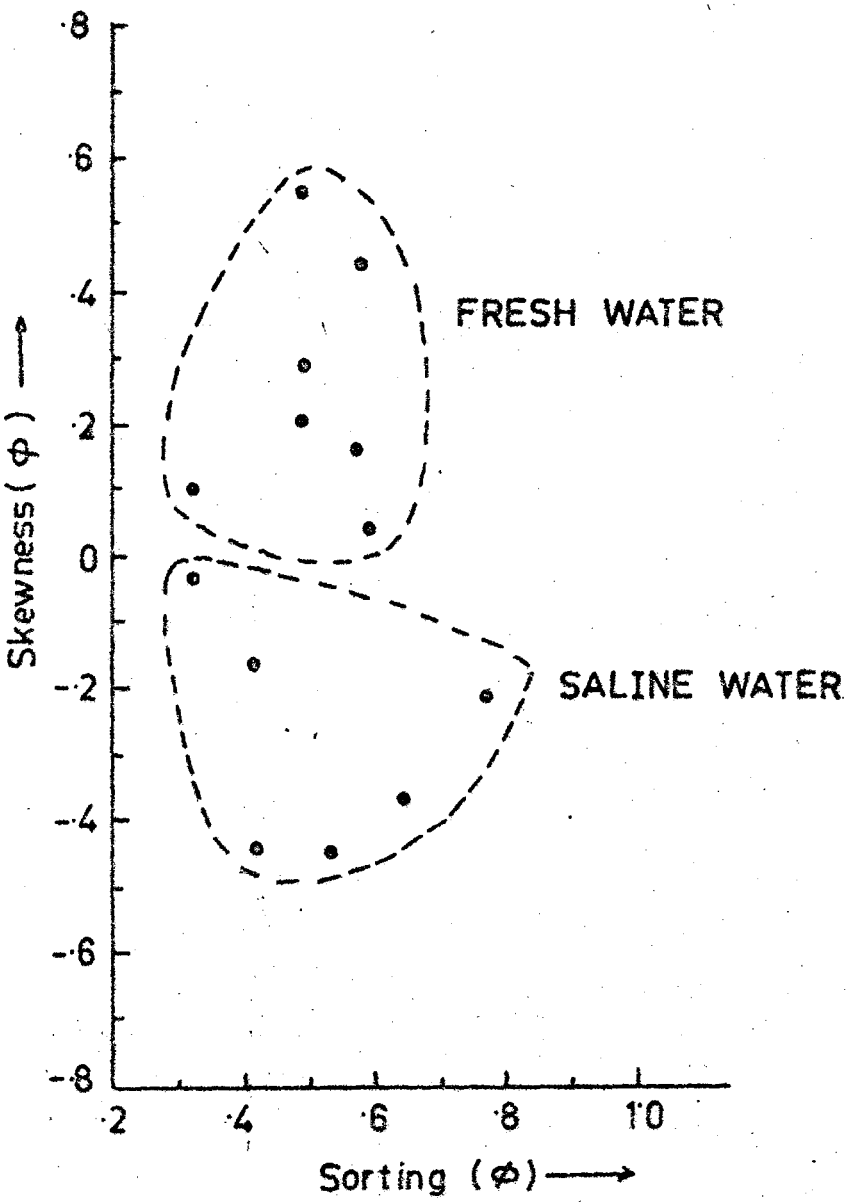


Fig. 14. Scatter plot, Skewness Vs Sorting of the bed-sediments

There is divided opinion about the exact nature of the boundary between the log-normal grain populations. Some workers believe that the population are truncated at their boundaries, while others maintain that populations are overlapping (Lambaise 1980). Middleton (1976) on the basis of data from several rivers suggested that grain populations are overlapping.

What does this mean

The cumulative frequency curves were drawn (Fig 15) assuming that the populations are log-normally distributed and overlapping. It shows that there is an essential difference in the grain size distributions at the estuary head and mouth.

It has been observed that the grain size is controlled by hydraulic and channel variables and weathering and abrasion (Knighton 1980). Sorting too is primarily the result of selective transport of various bed material sizes. Consequently the sorting phenomena is affected by all of the variables involved in sediment transport including flow, fluid and sediment properties. From the analysis of facts discussed above it seems that in the Hooghly estuary three environments prevail, first the fluvial environment - marked by well sorted finer grains, secondly a

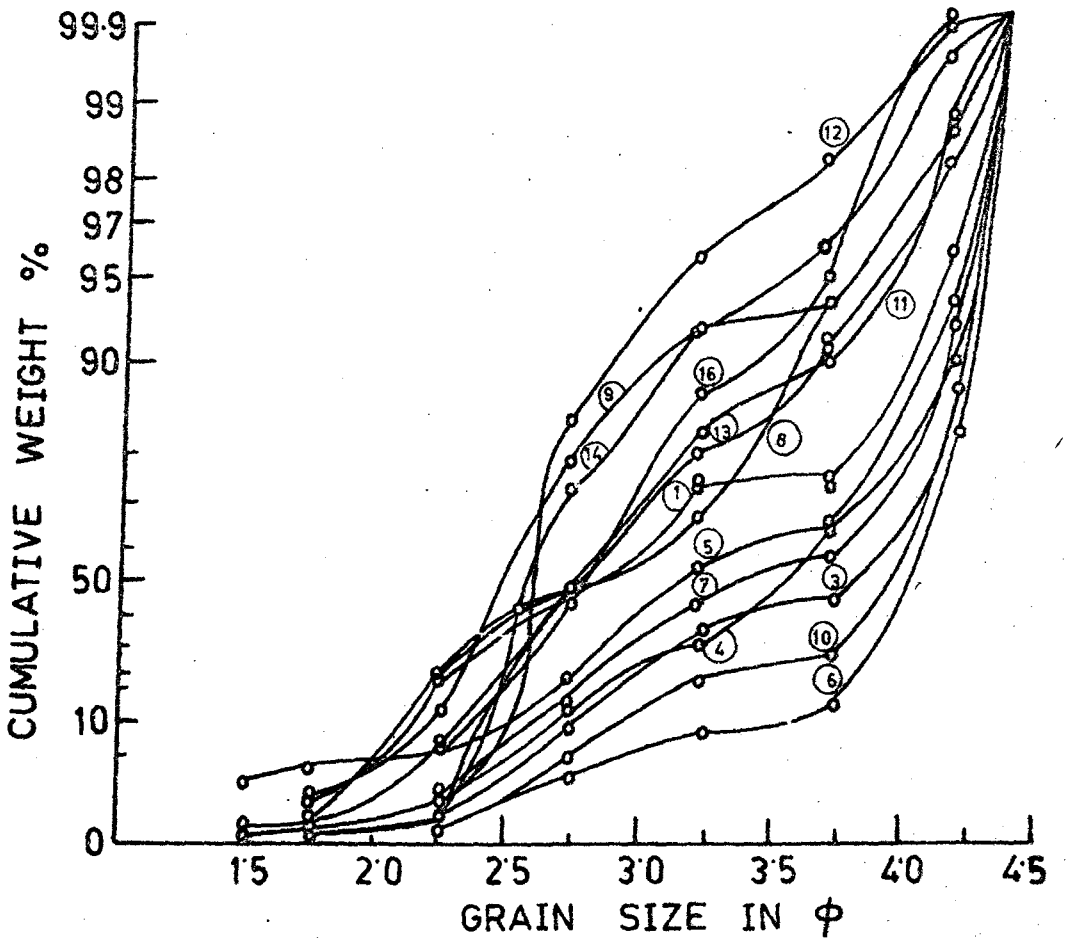


Fig. 15. The cummulative curves of the grain sizes of bed sediments

1. Dakshineswar ; 5. Budge - Budge ; 9. Haldia ;
3. Howrah ; 7. Diamond Harbour ; 11. Kuchuberia ;
4. Eden Garden ; 6. Bauria ; 8. Kukrahahati ;
10. Kakdwip ; 12. Ganga Sagar ; 13. Namkhana ;
14. Bakkhali ; 16. Digha ;

zone of low tidal effects and thirdly a zone of vigorous tidal influence - characterized by poorly sorted coarse grains. It seems that grain size distribution in the Hooghly estuary is governed mainly by the hydraulic influences not by weathering and abrasion, if we take into account the mineralogy of bed sediments discussed earlier.

However, no conclusive statement can be made, here, because the samples were restricted in number and the influence of tributaries of the Hooghly estuary was not taken into account. Besides this, the sediment transport mechanism needs a detailed study.

Organic content

The total organic content in the bed sediments is less than 1% except Dakshineswar and Namkhana, where we get 1.9% and 2.6% organic content respectively (Fig 16). At Kakdwip, Bakkhali, Ganga Sagar and Digha we get less than .02% organic content (See Appendix).

Rashid & Reinson (1979) pointed out that the organic matter distribution is probably related primarily to transport energy regime. They further suggested that gravitational settling is the main mechanism controlling organic distribution in the bottom sediments becaus e of (a) the strong correlation

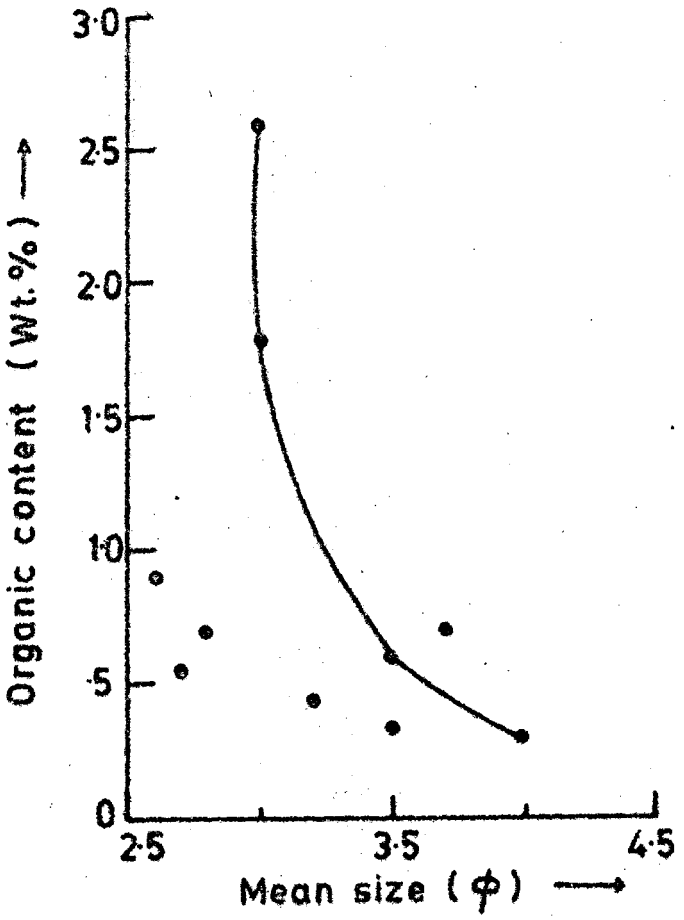


Fig.16. Organic content relation with grain size.

of organic distribution with fine grained sediment distribution in the inner bay; and (b) the apparent correlation of decreasing organic content with increasing distance from organic-effluent sources, and from natural land derived sources.

In the drowned river channel organic effluent laden discharge would be confined to the upper seaward moving fresh water layer, especially during ebb tide. Higher surface flow rates in the physically constricted channel would dampen the settling of large particulate organics, even while some flocculation was occuring, and would likely promote a settling size gradient downstream. At the drowned river mouth, channel flow suddenly becomes non-constrictive allowing more fine grained organics to be influenced by gravitational processes. Such organics would settle to the bottom in the relatively quiescent Inner Bay. Where estuarine circulation rates are lowest on incoming tide, some resuspension of this material probably occurs, allowing for further dispersal and redistribution.

In the Hooghly estuary, we see that organic content is closely related to the grain size. Finer sediments of the fresh water environments have higher percentage

of organic contents whereas the coarser sediments at the estuary mouth have low or only traces of organic content. At Dakshineswar, the sample was collected from bathing site of Kali Bari, which is a site of intense human-activity discharging organics in the water. Therefore, high (1.8%) organic content was found in the sediment over there. Besides this, the upper reaches of the Hooghly receives large quantity of industrial effluents, resulting in the increased organic content in this region. As we proceed downstream the influence of industrial effluents minimizes with a consequent decrease of organic content in the sediments. At Namkhama the river channel is mainly tidal, where water remains stagnant most of the time, allowing organic sediments to settle and decay. This may be one of the causes for higher organic content over there.

The qualitative study of the organic content was not done.

# CHAPTER V

## CONCLUSION

The Hooghly estuary receives its water and sediment supply from the Ganges-Brahmaputra system. Formerly the Hooghly flowed south-east from Calcutta near the exit of the present Tolly's nullah and joined the sea near Sagar Island. This channel, called the Adiganga is now reduced to a series of ponds and pools across the 24-Pargana close to Sagar Island. Now, the Hooghly flows south-southwest from Calcutta and then turns southeast towards Sagar Island. After the Damodar changed its course, the Hooghly at and above Calcutta has been shoaling up.

Based on the water chemistry, mineralogy of the bed sediments and grain size analysis, the Hooghly estuary may be divided into three distinct zones :

| | | |
|---|---|---|
| (a) | Low salinity zome | From Chuchura to Budge-Budge |
| (b) | Intermediate salinity zone | From Budge-Budge to Kukrahati |
| | | and |
| (c) | High salinity zone | From Kukrahati to Digha and onwards. |

Low Salinity Zone

This zone is dominated by the fresh water of high alkalinity (pH 8.5 - 8.4). The high pH values may be attributed to the additional buffering mechanism. The concentration of both the anions and cations are low except $HCO_3^-$ concentration. The high $HCO_3^-$ concentration of this zone may be due to the weathering of Kankar carbonate country rock and where industrial effluents disposal into the river. The conductivity varies from 0.4 mMHO/cm to 0.5 mMHO/cm. The concentration of the dissolved silica varies from 7.8 - 6.3 ppm. The $Ca^{++}/Mg^{++}$ ratio is 5.7.

Water of this region is suitable for the domestic, industrial and irrigational use.

Mineralogically, this zone is marked by the abundance of Kaolinite (4 - 64%); Quartz (1-59%) and Dolomite ( < 1-68%). Chlorite, illite and calcite are present in comparatively low quantity. Kaolinite and Dolomite have been reported in equilibrium with fresh water.

Sediments are fine grained. Therefore, organic content of the bed sediments are high.

Intermediate Salinity Zone

This is a zone of transition, where the mixing effects of the sea and fresh water is considerable. Increased conductivity (2.2 - 2.7 mMHO/cm) and anions and cations concentration mark this zone. The tidal effect is pronounced. Water is not suitable for domestic use. The pH (8.3) of water is comparatively lower than that of fresh water. The $Ca^{++}/Mg^{++}$ ratio is 1.44.

Among the clay minerals, illite becomes dominant (7-14%), Kaolinite decreases (11%) and chlorite remains less conspicuous (3%). Quartz constitutes the large part (50-51%) of the sediments; while feldspar remains only 5-10%. Among the carbonates calcite is dominant (10-26%) over dolomite (2-11%).

High Salinity Zone

This is the zone, where the sea water dominates over the fresh water with a consequent increase in anions and cations concentration. The pH (8 - 8.2) is lower than that of the fresh water. Conductivity increases to 27.2 mMHO/cm. The conductivity and the concentration of ions show that the Hooghly estuary extends even beyond Digha into the Bay of Bengal. Contai canal and the Subarnrekha river may also be responsible for this spread of the estuary. The dissolved silica concentration comes down to 0.6 ppm due

to its removal from the water. The mechanisms of the silica removal from the Hooghly water was not studied. But it is remarkable to note that 92% of dissolved silica of fresh water gets removed before reaching the sea. The $Ca^{++}/Mg^{++}$ ratio is 0.32.

Illite becomes the dominant (16-52%) clay mineral. Chlorite shows an increased abundance ( $<$ 1-5%). But the Kaolinite which is the dominamt clay mineral of the low salinity zone shows a drastic decrease in its abundance (1-12%). Similarly, Feldspar dominates the Quartz. The variation in the abundance of minerals may be attributed to their differential settling rates and grain-size. Usually Kaolinite settle first followed by Chlorite and Illite. Finer and lighter minerals may be swayed away into the bay by longshore currents etc. Clay minerals are fine grained so they are much affected by this phenomena. This may be one of the causes of the abundance of detritals (Quartz and feldspar) in the high salinity zone. The carbonates become less conspicuous (1-9%) in the sediments of this zone.

The grain-size becomes coarser because of longshore currents sweeping away the finer grains from coastal and near-coastal areas. Besides this, other factors related to hydraulic and channel variation are

also responsible for the poor sorting in this zone.

The lateral variation of the clay minerals in the estuary may be explained by the chemical alteration, differential flocculation and the physical sorting of sediment by size. The last one being the most important.

Sedimentation occurs throughout the estuary. The Hooghly is notorious for its sand banks and dangerous shoals of which the James and Mary sands, 56 Km below Calcutta and between the mouths of the Damodar and Rupnarayan, are well known.

Based on the specification given by Fairbridge (1980) for the estuary classification, the Hooghly may be considered as a low relief interdeltaic estuary.

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# APPENDICES

Table I: Cumulative Weight Percent of Grains Size Population Calculated from Original Wt. per cent

| Grain-Size PHI intervals Within bracket size in mm | Dakshineswar | | Howrah | | Eden Garden | | Budge-Budge | |
|---|---|---|---|---|---|---|---|---|
| | wt % | cum % | wt % | cum% | wt % | cum % | wt % | cum % |
| 1.5 - 2.0 (.35- .25) | 0.70 | 0.70 | - | - | 1.18 | 1.18 | 1.12 | 1.12 |
| 2.0 - 2.5 (.25- .177) | 0.39 | 1.09 | 0.21 | 0.21 | - | - | 0.83 | 1.95 |
| 2.5 - 3.0 (.177-.125) | 16.14 | 17.23 | 1.64 | 1.85 | 1.29 | 2.47 | 2.98 | 4.93 |
| 3.0 - 3.5 (.125- .08) | 25.61 | 42.84 | 7.96 | 9.81 | 8.1 | 10.57 | 14.02 | 18.95 |
| 3.5 - 4.0 (.08- .062) | 28.1 | 70.94 | 23.96 | 33.77 | 15.85 | 26.42 | 32.43 | 51.38 |
| 4.0 - 4.5 (.062-.044) | 1.61 | 72.55 | 6.97 | 40.74 | 15.91 | 42.33 | 11.5 | 62.88 |
| 4.5 to ~~below~~ Above 4.5 (.044 to below .044) | 22.98 | 95.53 | 46.24 | 86.98 | 47.45 | 89.78 | 30.69 | 93.56 |
| ~~Below~~ Above 4.5 (below .044) | 5.80 | 101.33 | 13.02 | 100.00 | 10.21 | 99.99 | 6.43 | 99.99 |
| T O T A L | 101.33 | | 100.00 | | 99.99 | | 99.99 | |

(contd..

Table I: Cumulative Weight Percent of Grain Size Population Calculated from Original wt. per cent

(contd..)

| Grain Size PHI intervals. Within bracket size in mm | Bauria | | Diamond Harbour | | Kukrahati | | Kakdwip | | Haldia | |
|---|---|---|---|---|---|---|---|---|---|---|
| | wt % | Cum % | wt % | cum% | wt % | cum % | wt % | cum % | wt % | cum % |
| 1.5 - 2.0 (.35 - .25) | - | - | - | - | - | - | - | - | - | - |
| 2.0 - 2.5 (.25- .177) | - | - | 0.46 | 0.46 | 0.74 | 0.74 | - | - | 3.27 | 3.27 |
| 2.5 - 3.0 (.177- .125) | 0.40 | 0.40 | 2.15 | 2.61 | 3.65 | 4.39 | 0.53 | 0.53 | 8.65 | 11.92 |
| 3.0 - 3.5 (.125- .08) | 3.44 | 3.84 | 11.76 | 14.37 | 14.21 | 18.6 | 4.43 | 4.96 | 66.25 | 78.17 |
| 3.5 - 4.0 (.08- .062) | 4.22 | 8.06 | 27.32 | 41.69 | 28.63 | 47.23 | 11.73 | 16.72 | 13.44 | 91.61 |
| 4.0 - 4.5 (.062- .044) | 5.1 | 13.16 | 16.3 | 57.99 | 18.7 | 65.93 | 7.81 | 24.53 | 0.63 | 92.24 |
| 4.5 to below 4.5 (.044 to below .044) | 68.65 | 81.81 | 34.6 | 92.59 | 27.1 | 93.03 | 63.14 | 87.67 | 6.2 | 98.44 |
| Below 4.5 (below .044) | 18.21 | 100.02 | 7.4 | 99.99 | 6.97 | 100.00 | 12.36 | 100.03 | 1.56 | 100.00 |
| T O T A L | 100.02 | | 99.99 | | 100.00 | | 100.03 | | 100.00 | |

(contd...

Table I: Cumulative Weight Per cent of Grain Size Population Calculated from Original wt. per cent

(contd..)

| Grain Size PHI intervals. Within bracket size in mm | Kuchuberia | | Ganga Sagar | | Namkhana | | Bakkhali | | Digha | |
|---|---|---|---|---|---|---|---|---|---|---|
| | wt % | cum % | wt % | cum % | wt % | cum % | wt % | cum % | wt % | cum % |
| 1.5 - 2.0 (.35 - ,25) | 0.31 | 0.31 | 0.26 | 0.26 | 0.69 | 0.69 | - | - | 3.48 | 3.48 |
| 2.0 - 2.5 (.25- .177) | 0.56 | 0.87 | 0.11 | 0.37 | 0.48 | 1.17 | - | - | 0.34 | 3.82 |
| 2.5 - 3.0 (.177- .125) | 5.31 | 6.18 | 0.71 | 1.08 | 1.15 | 2.32 | 0.59 | 0.59 | 1.46 | 5.28 |
| 3.0 - 3.5 (.125- .08) | 41.8 | 47.98 | 81.8 | 82.88 | 42.39 | 44.71 | 70.99 | 71.58 | 37.33 | 42.61 |
| 3.5 - 4.0 (.08- .062) | 33.4 | 81.38 | 12.2 | 95.18 | 34.47 | 79.18 | 19.64 | 91.22 | 42.73 | 85.34 |
| 4.0 - 4.5 (.062- .044) | 8.3 | 89.68 | 2.92 | 98.1 | 11.24 | 90.42 | 4.66 | 95.88 | 9.30 | 94.64 |
| 4.5 to below 4.5 (.044 to below .044) | 8.97 | 98.65 | 1.65 | 99.75 | 7.66 | 98.08 | 3.48 | 99.36 | 5.18 | 99.82 |
| Below 4.5 (below .044) | 1.33 | 99.98 | 0.38 | 100.13 | 1.9 | 99.88 | 0.61 | 99.97 | 0.16 | 99.98 |
| T O T A L | 99.98 | | 100.13 | | 99.88 | | 99.97 | | 99.98 | |

Table II: PHI Value of Grain Sizes Calculated From the Cumulative Frequency Curves for Different Percenticles

| Cumulative Percentage | Dakshi-neswar | Howrah | Eden Garden | Budge-Budge | Bauria | Diamond Harbour | Kukra-hati |
|---|---|---|---|---|---|---|---|
| P 95% | 2.0 | 2.6 | 2.5 | 2.2 | 3.0 | 2.5 | 2.0 |
| P 84% | 2.2 | 3.0 | 2.9 | 2.7 | 3.8 | 2.8 | 2.2 |
| P 75% | 2.4 | 3.1 | 3.2 | 2.9 | 3.9 | 3.0 | 2.3 |
| P 50% | 2.9 | 3.9 | 3.6 | 3.2 | 4.0 | 3.5 | 2.8 |
| P 25% | 3.8 | 4.1 | 4.0 | 3.8 | 4.2 | 4.0 | 3.4 |
| P 16% | 4.0 | 4.2 | 4.1 | 4.0 | 4.3 | 4.1 | 3.0 |
| P 5% | 4.2 | 4.3 | 4.3 | 4.3 | 4.4 | 4.4 | 3.9 |

(contd....

Table II: PHI Value of Grain Sizes Calculated from the Cumulative Frequency Curves for Different Percentiles

| Cumulative Percentage | Haldia | Kakdwip | Kuchu-beria | Ganga Sagar | Nam-khana | Bakkhali | Digha |
|---|---|---|---|---|---|---|---|
| P 95% | 2.1 | 2.8 | 2.2 | 2.4 | 2.3 | 2.4 | 2.2 |
| P 84% | 2.3 | 3.2 | 2.4 | 2.0 | 2.5 | 2.5 | 2.5 |
| P 75% | 2.3 | 3.8 | 2.5 | 2.6 | 2.6 | 2.5 | 2.6 |
| P 50% | 2.5 | 4.0 | 2.8 | 2.6 | 2.8 | 2.6 | 2.8 |
| P 25% | 2.7 | 4.2 | 3.1 | 2.6 | 3.2 | 2.8 | 3.0 |
| P 16% | 2.9 | 4.2 | 3.2 | 2.8 | 3.6 | 3.0 | 3.2 |
| P 5% | 3.9 | 4.4 | 3.0 | 3.2 | 4.0 | 3.6 | 3.8 |

TABLE III: Formula Used For Graphic Measures (After Folk and Ward, 1957)

| Name | Graphic Formula | Remarks |
|---|---|---|
| Mean | $Me_{\phi} = \frac{(\phi_{16} + \phi_{50} + \phi_{84})}{3}$ | All three measures of central tendency reflect average kinetic energy of depositing medium plus size distribution of available sediment. |
| Median | $Md_{\phi} = \phi_{50}$ | |
| Sorting | Inclusive graphic standard deviation $S_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$ | Measures dispersion, which is dependent upon velocity variation plus bimodality. |
| Skewness | Inclusive graphic skewness $SK_I = \frac{\phi_{84}+\phi_{16}-2\phi_{50}}{2(\phi_{84}-\phi_{16})} + \frac{\phi_{95}+\phi_5-2\phi_{50}}{2(\phi_{95}-\phi_5)}$ | Measures asymmetry, the direction of "tail" which are widely believed to have environmental significance. Skewness varies from +1 (positive) to 0 (symmetrical) to -1 (negative). |
| Kurtosis | $K_G = \frac{(\phi_{95} - \phi_5)}{2.44(\phi_{75}-\phi_{25})}$ | Measures peakedness. Graphic measure is ratio of sorting of centered 90 per cent to centered 50 per cent. $K_G = 1$ for normal curve, $K_G > 1$ for peaked curve and $K_G < 1$ for flattened curve. |

Table IV: Various parameters of sediment's grain size distribution using the formula of Folk & Ward (1957)

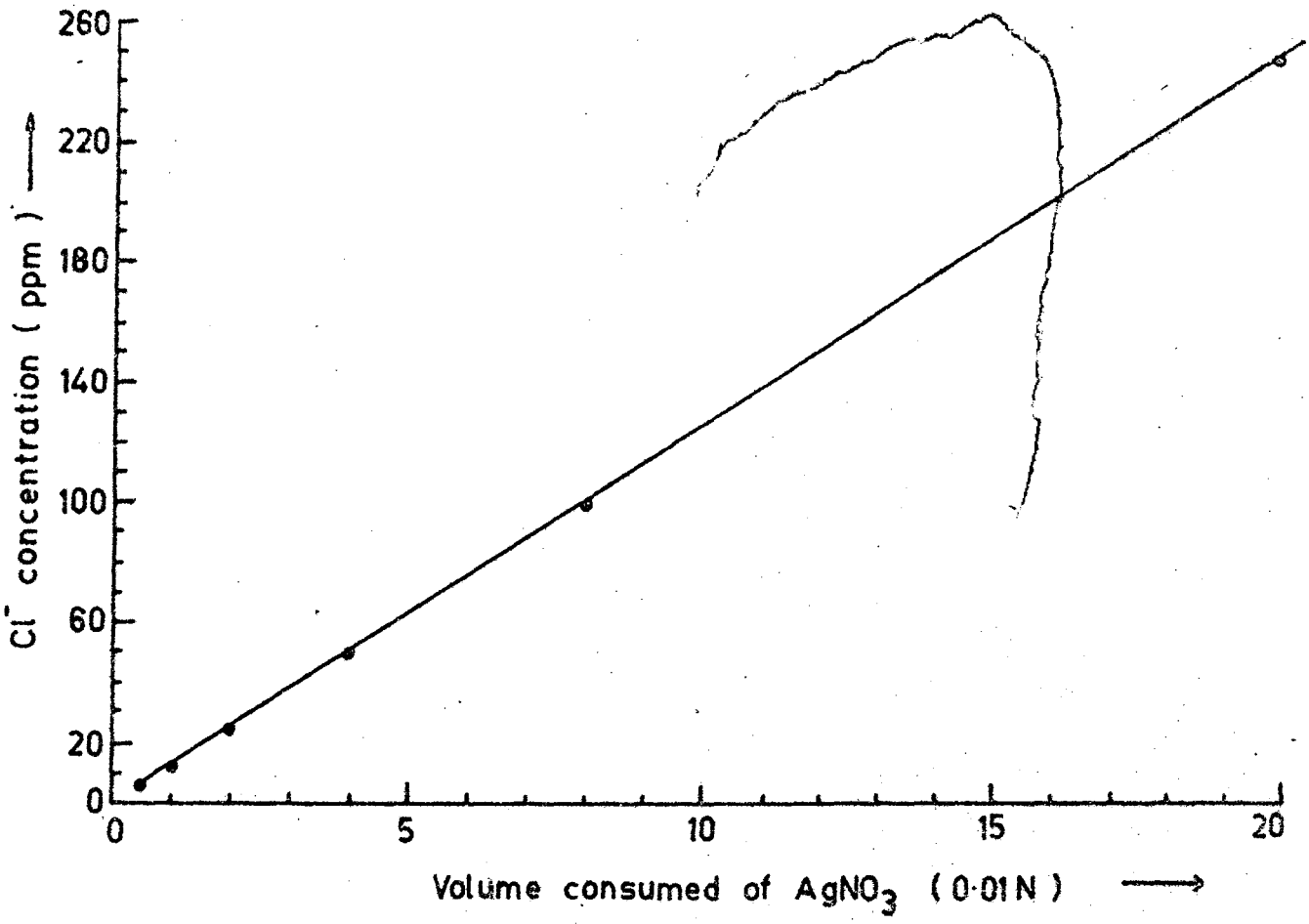
| Parameters | Dakshi-neswar | Howrah | Eden Garden | Budge-Budge | Bauria | Diamond Harbour | Kukra-hati |
|---|---|---|---|---|---|---|---|
| Graphic Mean | 3.0 | 3.7 | 3.5 | 3.2 | 4.0 | 3.5 | 2.7 |
| Median | 2.9 | 3.9 | 3.6 | 3.2 | 4.0 | 3.5 | 2.8 |
| Sorting | 0.77 | 0.58 | 0.57 | 0.64 | 0.49 | 0.59 | 0.49 |
| Skewness | -0.22 | 0.44 | 0.16 | -0.17 | 0.29 | 0.04 | 0.20 |
| Kurtosis | 0.65 | 0.66 | 0.98 | 0.88 | 1.91 | 0.70 | 0.71 |
| Total organic content (wt%) | 1.80 | 0.71 | 0.34 | 0.43 | 0.30 | 0.60 | 0.55 |

(contd....

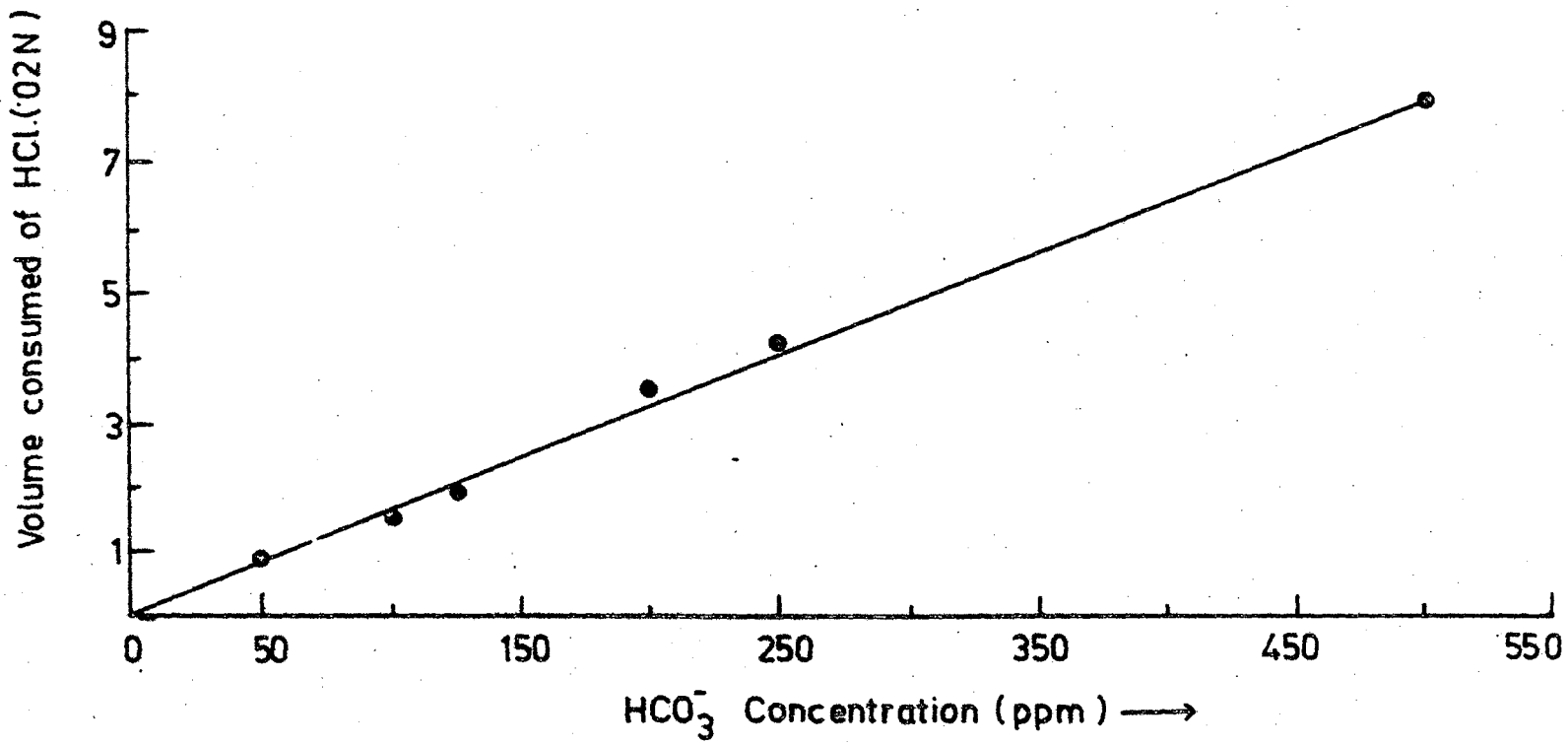
Table IV: Various parameters of sediment's grain size distribution using the formula of Folk & Ward (1957)

(contd...)

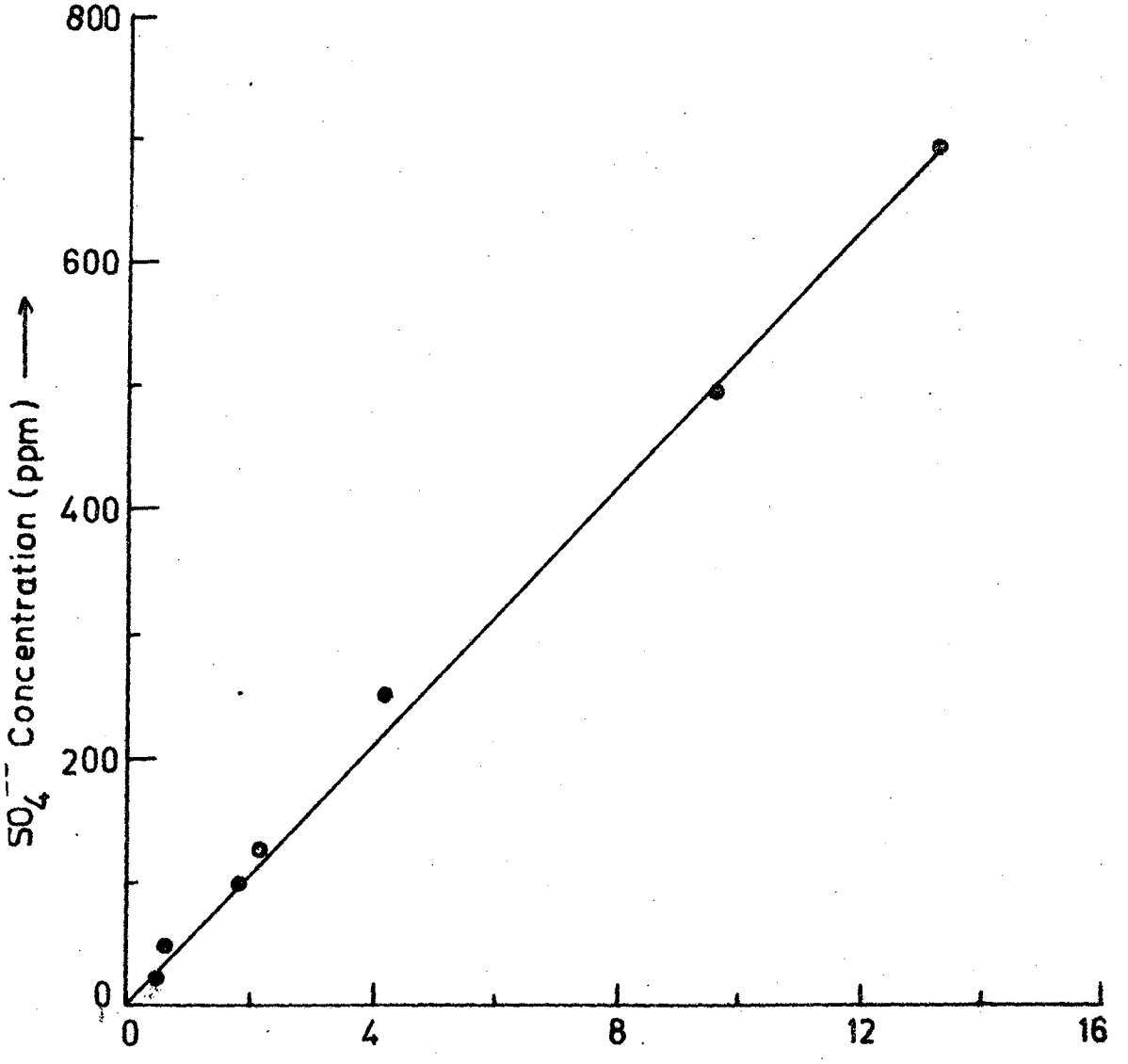
| Parameters | Haldia | Kakdwip | Kuchu-beria | Ganga Sagar | Namkhana | Bakkhali | Digha |
|---|---|---|---|---|---|---|---|
| Graphic Mean | 2.6 | 3.8 | 2.8 | 2.5 | 3.0 | 2.7 | 2.8 |
| Median | 2.5 | 4.0 | 2.8 | 2.6 | 2.8 | 2.6 | 2.8 |
| Sorting | 0.42 | 0.49 | 0.32 | 0.32 | 0.53 | 0.30 | 0.41 |
| Skewness | -0.44 | 0.55 | 0.1 | -0.03 | -0.45 | -0.72 | -0.16 |
| Kurtosis | 2.0 | 1.46 | 0.56 | 4.1 | 1.13 | 1.58 | 1.39 |
| Total organic content (wt%) | 0.90 | 0.02 | 0.71 | - | 2.6 | - | 0.01 |



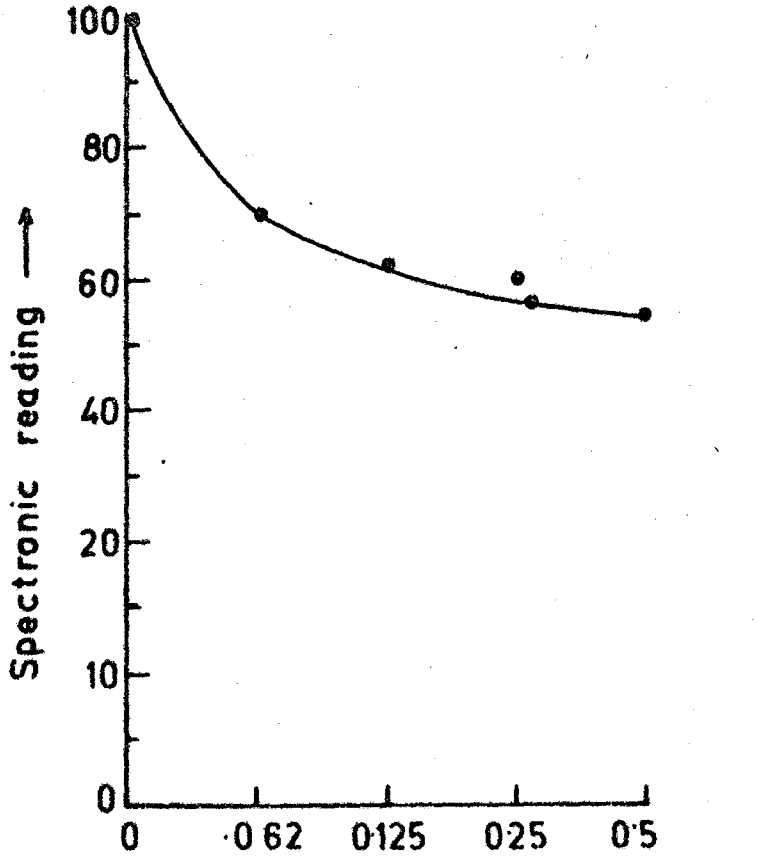

Plot of $Cl^-$ standard solution



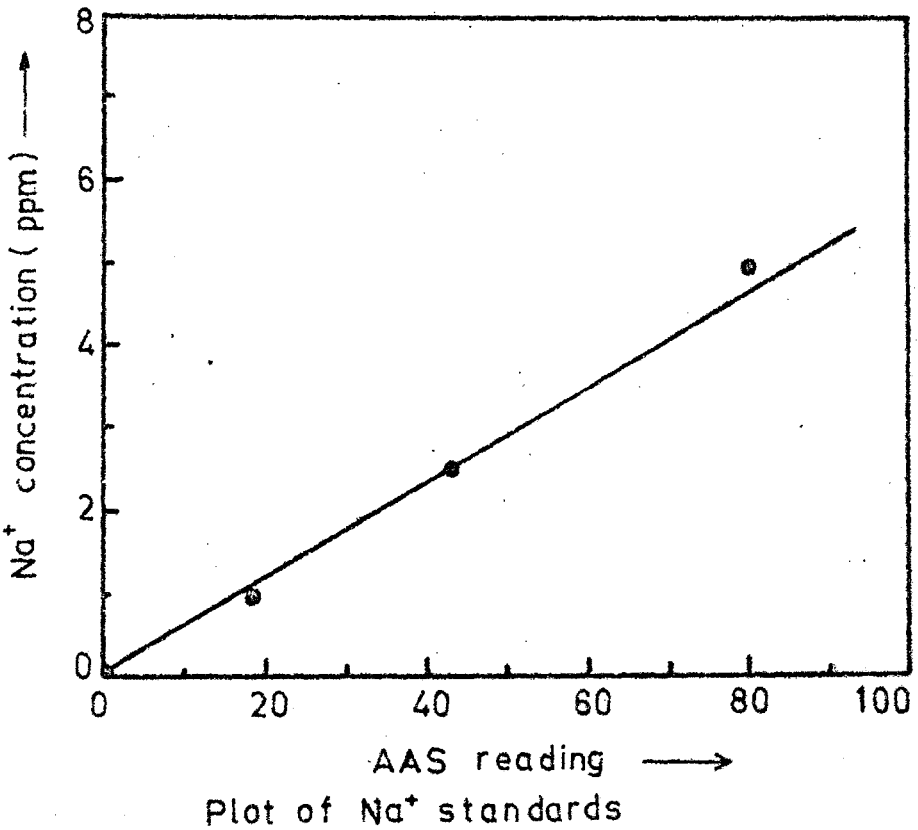

Plot of standard solution of $HCO_3^-$.



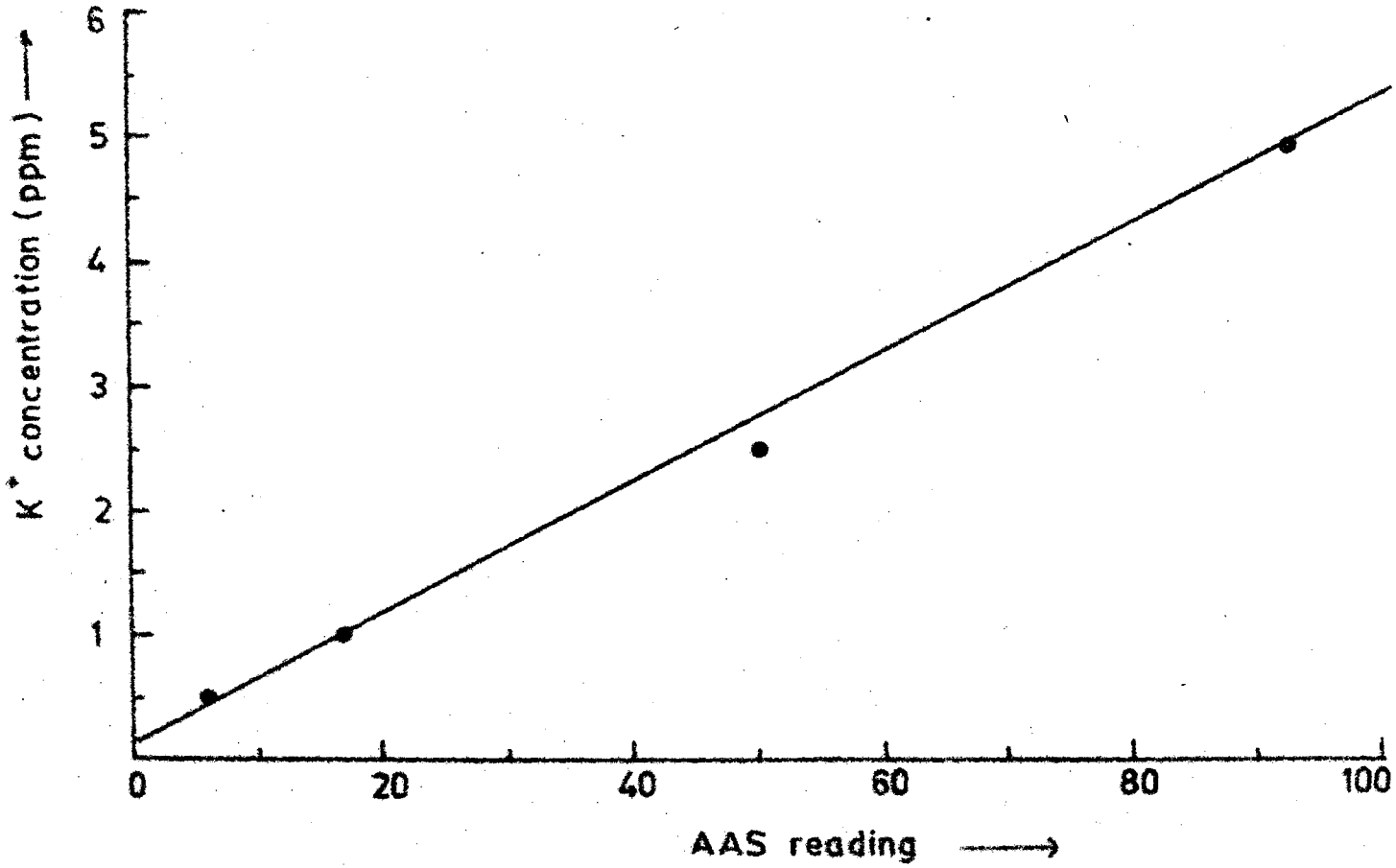

Plot of standard solution of $SO_4^{--}$



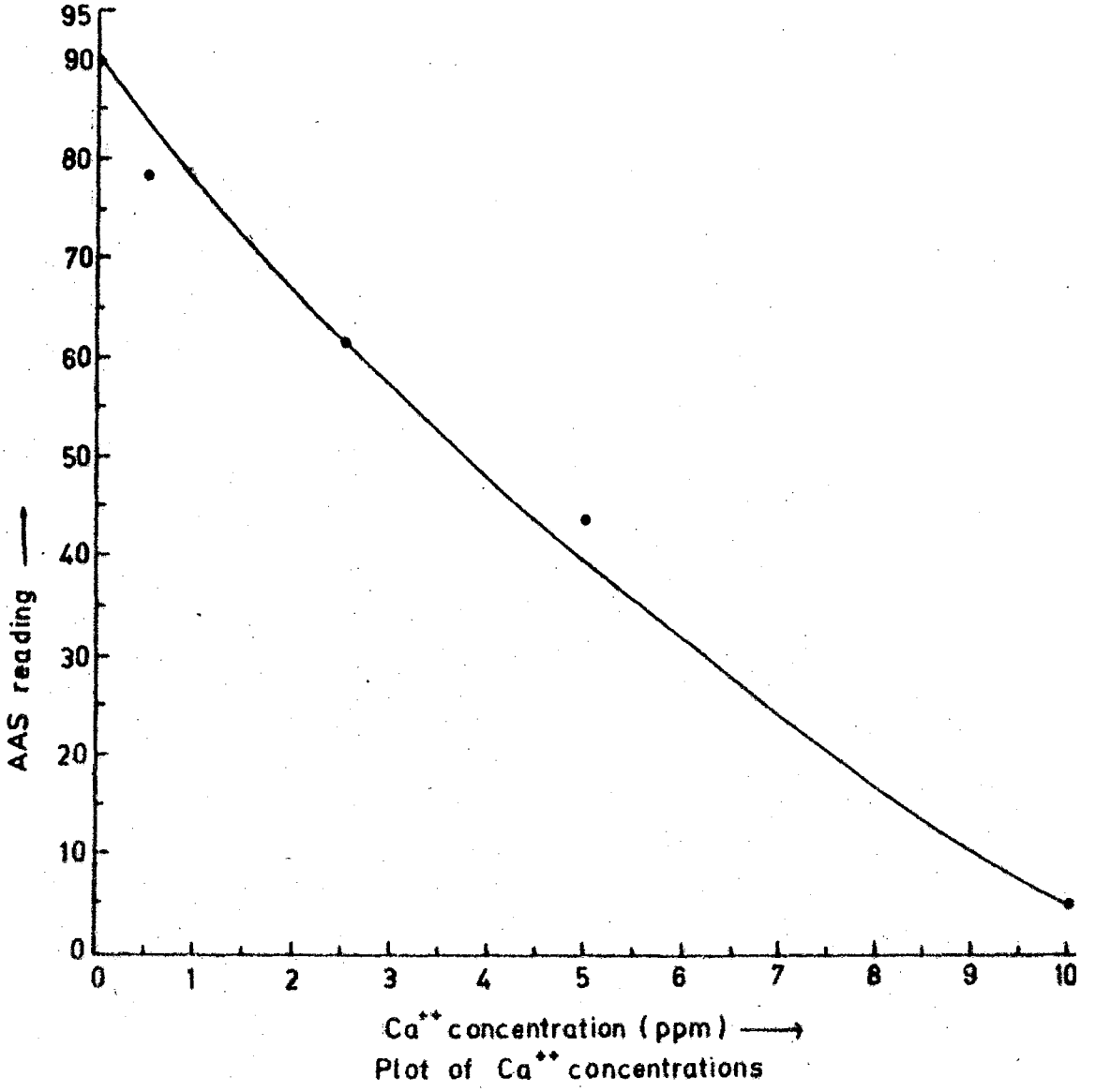

Plot of $PO_4^{---}$ standards.



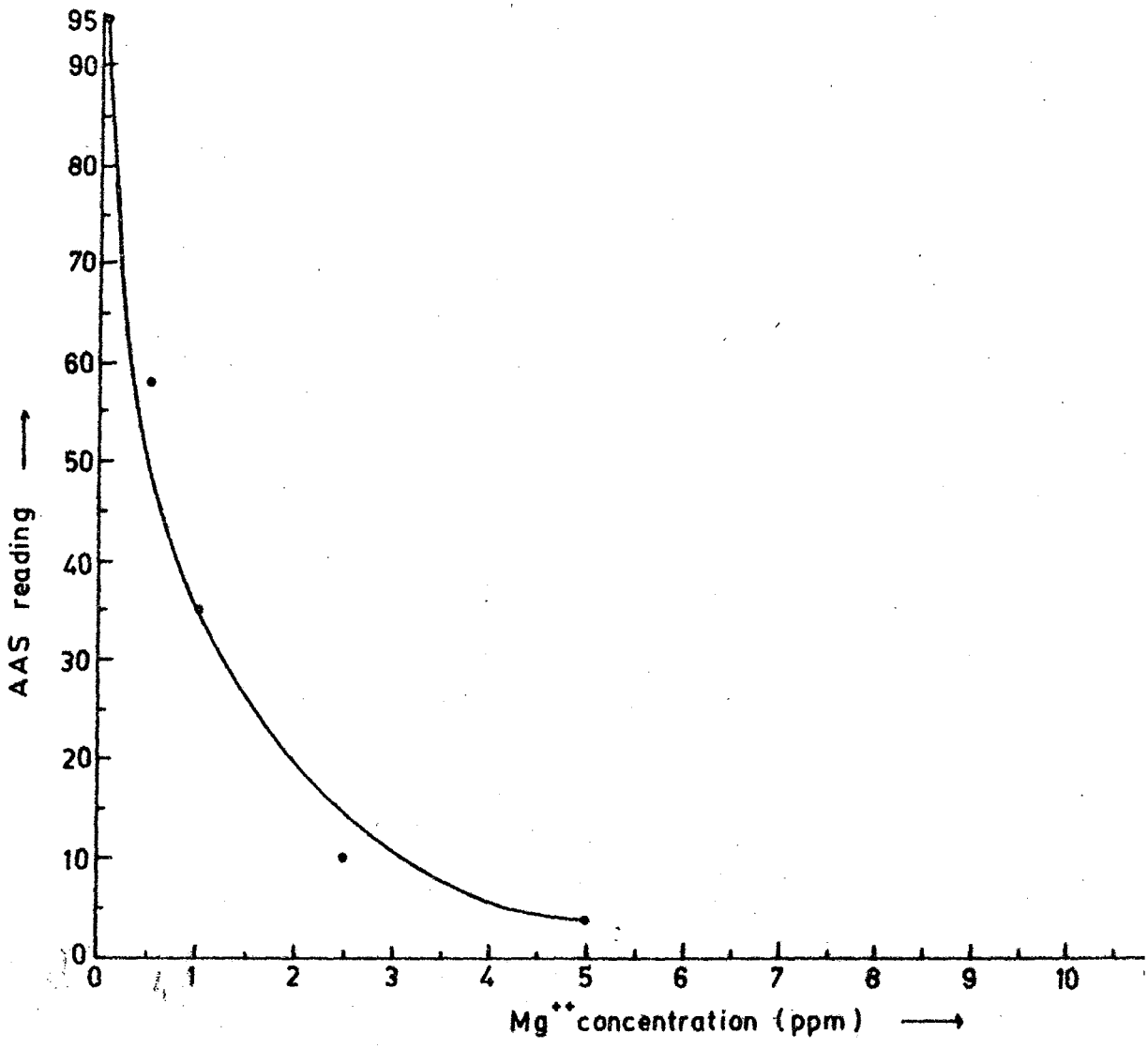

Plot of $Na^+$ standards



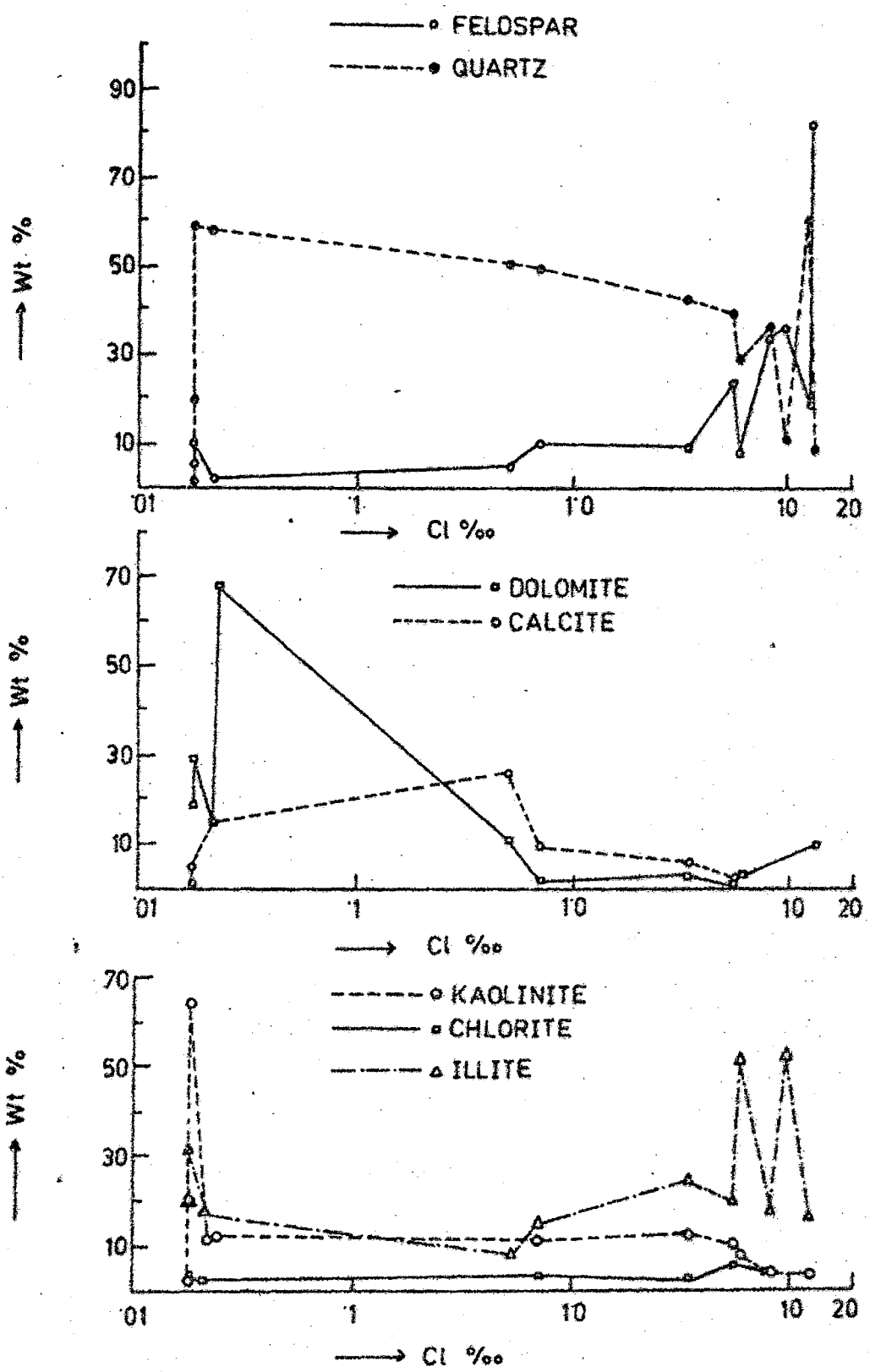

Plot of $K^+$ standards.



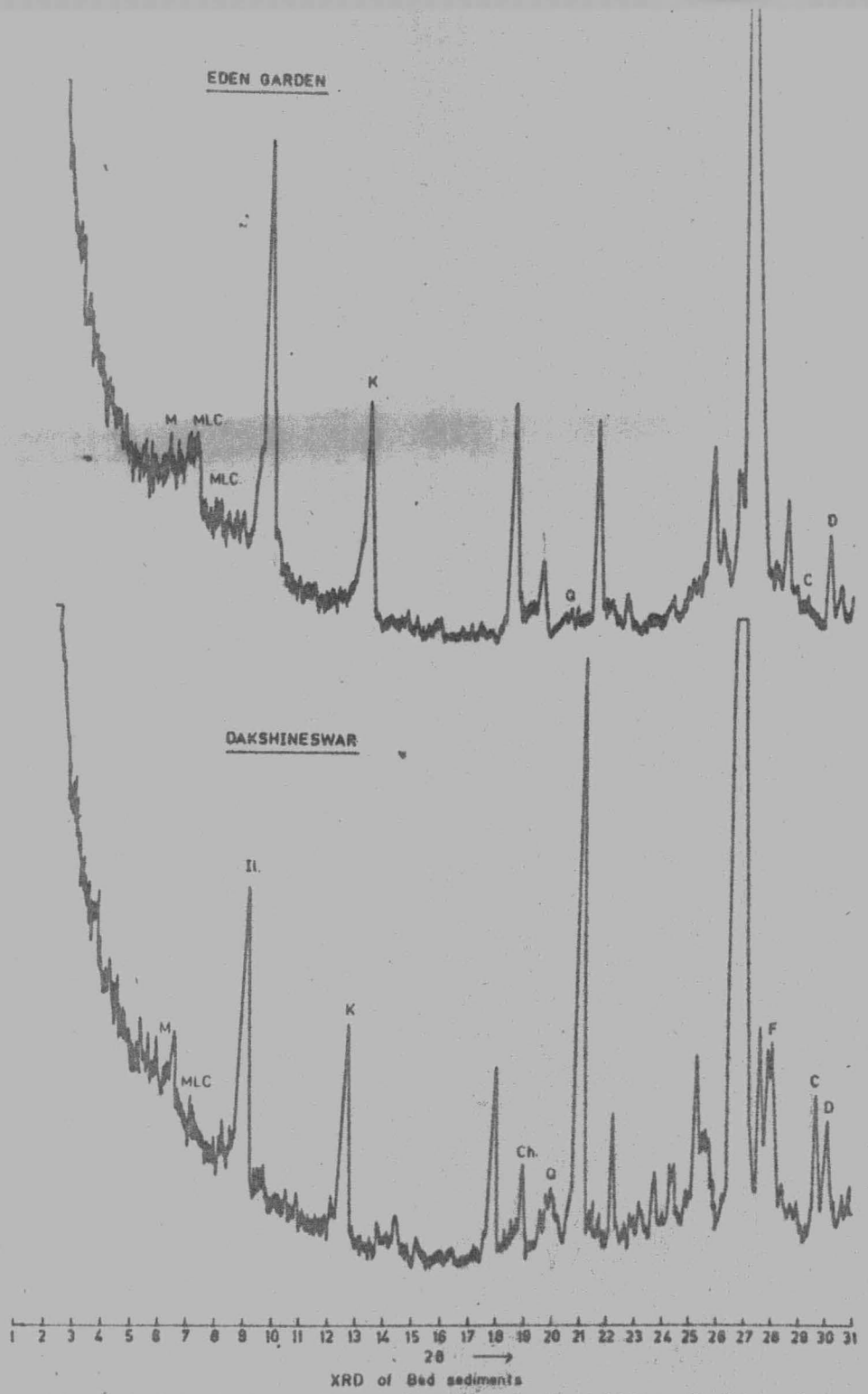

Plot of $Ca^{++}$ concentrations




Standard plot of $Mg^{++}$ concentrations

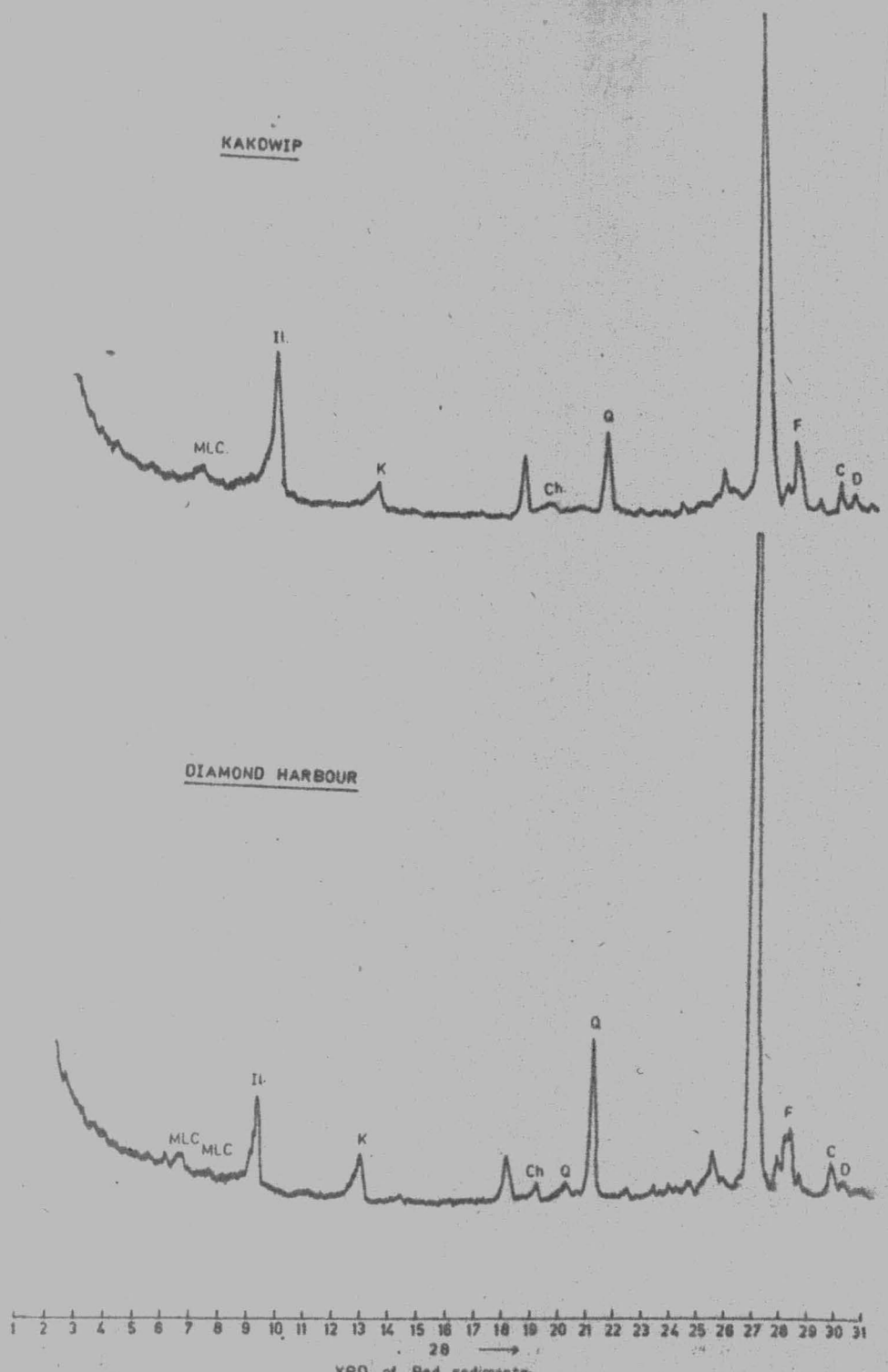



Variation of minerals with chlorinity.



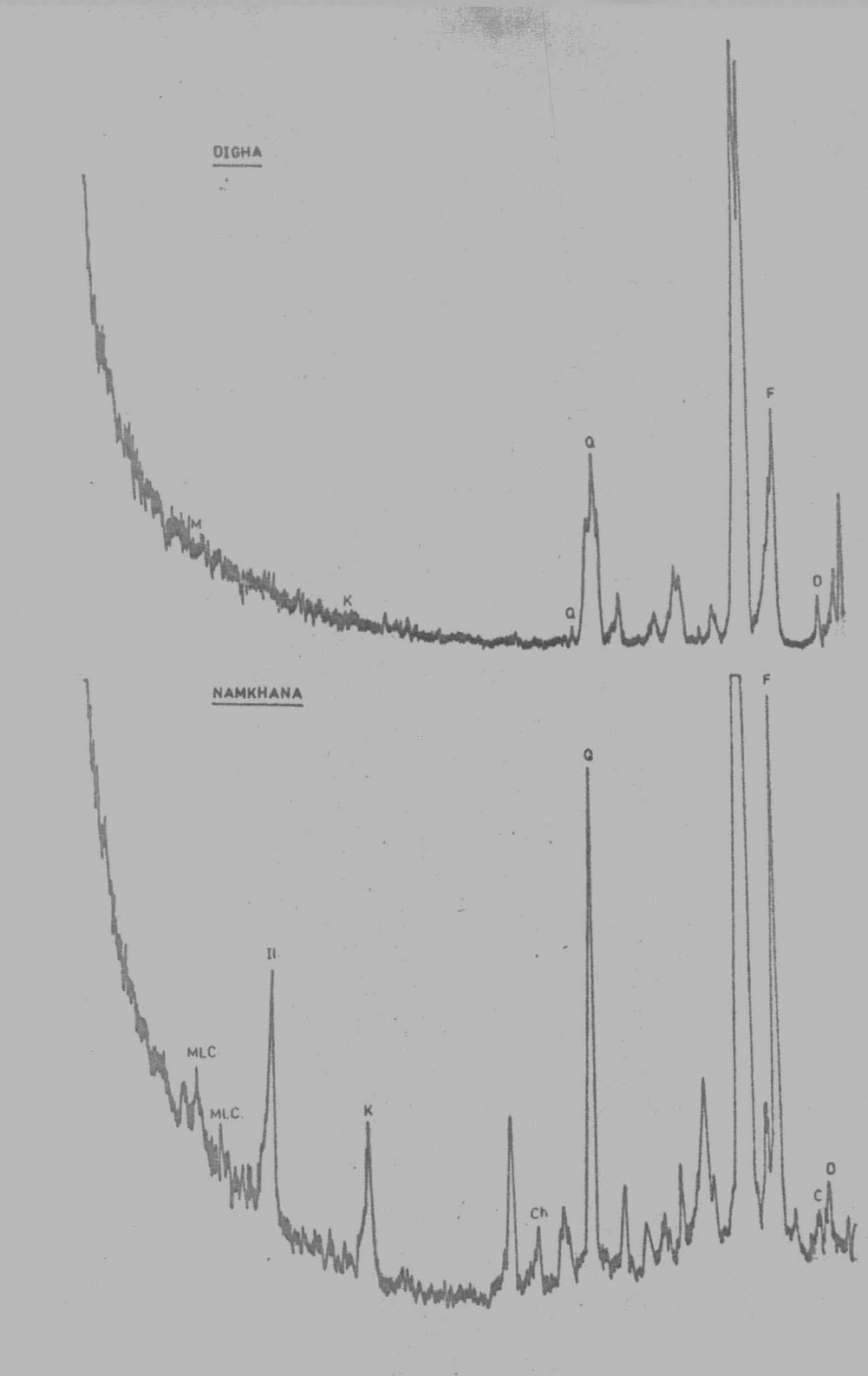

XRD of Bed sediments

Illite = Il ; Kaolinite = K , Chlorite = Ch, Montmorillonite = M , Quartz = Q , Feldspar = F ; Calcite = C , Dolomite = D , Mixed layer clay = MLC




XRD of Bed sediments

Illite = Il ; Kaolinite = K ; Chlorite = Ch; Moutmorillomite = M ; Quartz = Q ; Feldspar = F ; Calcite = C ; Dolomite = D ; Mixed layer clay = MLC.




XRD of Bed sediments

Illite = Il ; Kaolinite = K , Chlorite = Ch; Moutmorillomite = M ; Quartz = Q ; Feldspar = F ; Calcite = C ; Dolomite = D ; Mixed layer clay = MLC.