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IMPORTANT ASPECTS OF ESTUARINE SEDIMENT CHEMISTRY FOR BENTHIC ECOLOGY

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INTRODUCTION

Estuarine sediments form the substrate upon which benthonic plants and animals subsist, and ecologists have shown clearly that different plant and animal associations thrive on specific kinds of substrates. The aerial distribution of such associations follows that of the favored substrate and we may conclude that the nature of the substrate is an ecological variable much the same as the more familiar variables such as temperature, salinity, light intensity, etc. We can compare the situation to the one on land where plant ecologists have shown the close correlation between climax communities and specific climatic variables and their affiliated soil types. Small scale variations in plant associations within such a climax community are correlated with micro-relief and soil characteristics. The problem in extending this viewpoint to the benthonic environment is to employ descriptive parameters that define variations in the substrate in an ecologically useful way. Up to this time the substrate has been characterized in terms of its gross texture or its total organic carbon content. I shall describe below some other parameters that are useful in defining sedimentary substrates for ecological purposes.

Dr. Salomon already described the general affinities that exist between terrestrial soils and estuarine sediments. He pointed out that sediment essentially is soil material that has been transported from its place of origin to a new environment. I shall discuss the properties of estuarine sediments that are peculiarly their own. Some of these properties they inherit from their soil parents, while others are a result of adjustments that take place within the estuarine environment itself.

In general, estuarine sediments differ in two very important respects from soils. First, the physical forces of fluid flow that are responsible for transporting soil materials to the estuarine environment are of such intensity that they break up the original structure and texture and redistribute its components to different parts of the new environment. Second, the soil materials respond to chemical conditions in the estuary by adjustments that may transform them. Such readjustments take several forms: ion exchange reactions, recrystallization, assumption of new bulk properties, changes in associated microflora, different pore water chemistry.

BULK PROPERTIES AND TEXTURE

Terrestrial soils typically consist of granular mineral particles that possess a wide range of sizes. They contain sand, silt and clay in abundance and, for this reason, they can be characterized as poorly sorted. When soil is eroded by a stream, the textural constituents are separated and carried by the stream in different ways. The coarsest particles are carried close to the bed, while the finest particles are distributed throughout the water column. The concentration of suspended

matter increases from the free water surface towards the bottom, and the stream, by distributing its load at different levels and transporting each at different rates, causes a differentiation of the terrestrial source material. Upon entering saline water, freshwater streams encounter the familiar net non-tidal estuarine circulation pattern in its various forms. The bedload and the suspension load of the freshwater stream are dispersed to different parts of the estuarine system by this circulation. In addition, wave and current action within the estuarine environment locally redistribute and rework the sediment supplied and sort it into well differentiated sediment types, each of which is relatively homogeneous. This is the way that the familiar textural variations typical of estuarine substrates are formed. Characterization of such textural types, and study of their distribution is, of course, a valuable aid in the study of benthic ecology.

Terrestrial soils typically are differentiated vertically into horizontal layers that differ from one another physically and chemically (Figure 1a). Such a vertically differentiated section is called a soil profile. It develops as a result of the downward percolation of rain water through the porous unconsolidated mantle, and as a result of the hydrolytic activity of such waters upon silicate minerals that are fundamentally unstable under the oxidizing and aqueous atmospheric conditions that exist at the earth's surface. Soluble constituents from such minerals are removed completely while the residues form clayey hydroxides and alumino-silicates. Many such clayey products are physically transported from the upper horizons to the lower, enhancing the textural distinction between horizons.

A profile develops in vertical sections of estuarine sediments (Figure 1b), but the processes forming it are basically dissimilar to the ones operating on land. There is no fundamental textural differentiation between horizons, because downward percolation of interstitial water does not occur. In fact, diffusion and exchange proceed upward toward the free water overlying the sediment. The profile is primarily a chemical and biological adjustment between the oxygenated and mobile overlying water and the de-oxygenated and immobile sediment that exists at depth. Immediately adjacent to the overlying water is a thin layer of semi-fluid, oxidized sediment that is swept temporarily into suspension by the strongest currents. Below is a thin layer of olive gray sediment and then one of very dark gray or black mud which represent the zones in which microbial activity reaches a peak. Where the water movements above the bottom are restricted and there is minimum diffusion of oxygen, etc. from the water to the sediment, these zones may occur at the very surface. It is across this fundamental sedimentary boundary that nutrients and trace elements diffuse from the sediment into the overlying water. Below is a zone typically medium to light gray in color which represents sediment that has passed beyond the zone of maximum microbial decomposition and chemical activity.

The profile illustrated in Figure 1b is found throughout the estuarine region. In places it is modified by erosion at its surface. In the uppermost parts of estuaries thin layers of sandy sediment may be interstratified in a profile that fundamentally consists of silt and clay. In shallow water the mud is swept away and the sand which remains normally does not show the typical estuarine sediment profile. As has been noted

SOIL

SEDIMENT

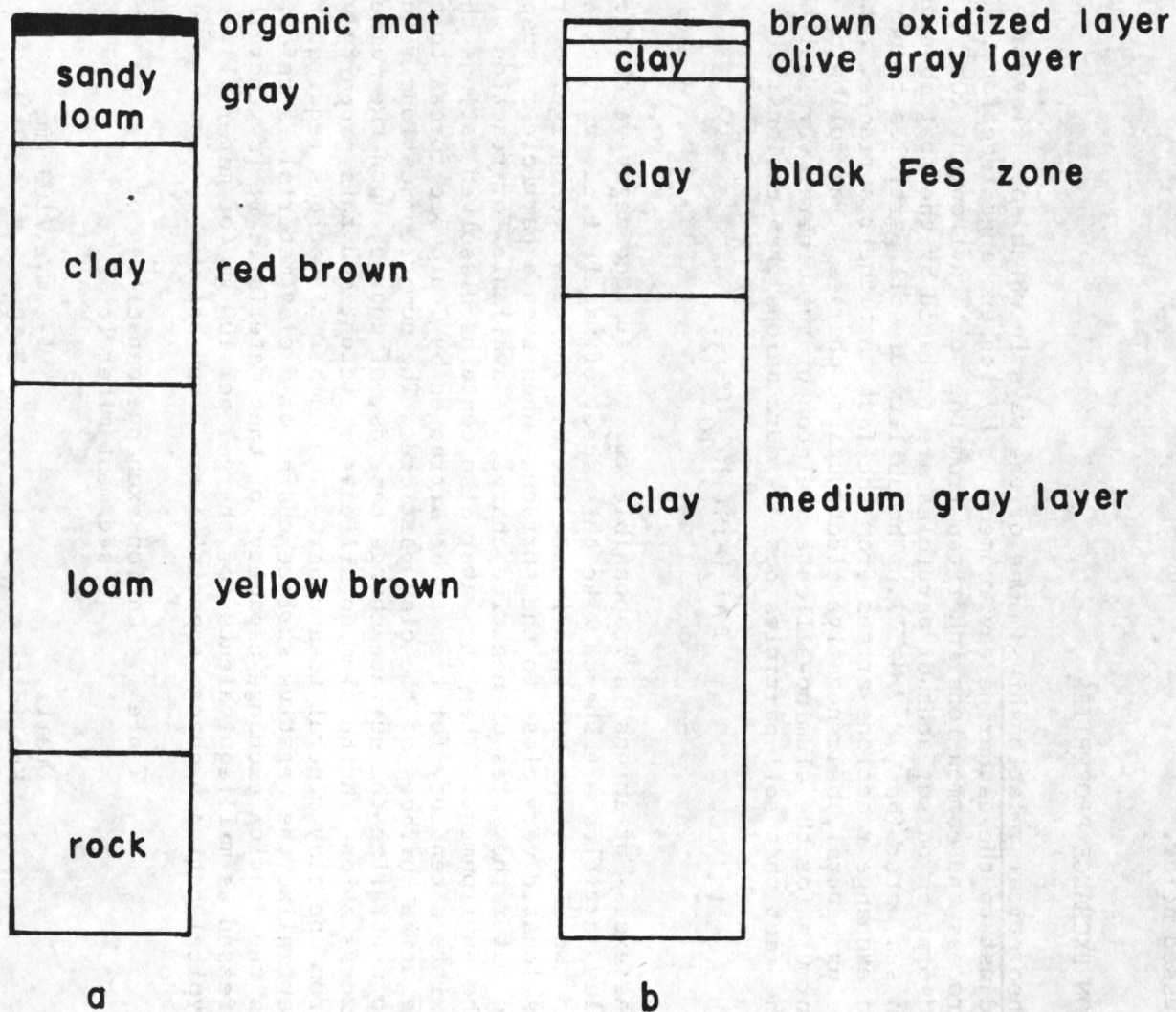
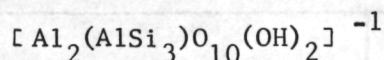


Figure 1. Soil and sediment profiles compared.

above, the depths of the various horizons below the sediment surface are a function of ventilation in the overlying water, and their position shifts with changes in these conditions. The estuarine substrate can be characterized from place to place by a detailed description of the sediment profile to a depth of several inches. Even this simple observation is sufficient to distinguish many micro-environments in estuaries, because the profile is an integrated spectrum of all the physical and chemical parameters of estuarine sediments, which are discussed below.

ION EXCHANGE PROPERTIES

Theoretical relationships: One of the ways in which soil clay materials adjust to the estuarine environment is by ion exchange reactions. In this process the common ions inherited from the soil environment (Ca^{++} , H^+) by adsorption on surfaces of particles are replaced by the most abundant ions in sea water (Na^+ , K^+ , Mg^{++}). The ability of soil particles to participate in exchange reactions arises from the fact that their surfaces, rather than being neutral, bear negative electrostatic charges. The following chemical formula for the alumino-silicate skeleton of the mineral vermiculite reflects the fact that soil particles possess more anions than cations:



The excess of anions is responsible for the surface negative charge. Clay particles are shaped like this sheet of paper, i.e., very extensive in two dimensions but thin in the third. The negative charge, therefore, is located very close to the surface. When such a particle is suspended in water the sites of negative charge are available for reaction with the environment. When the water also contains dissolved cations there exists a tendency for them to be attracted by Coulombic forces to the negative surfaces of the clay particle. The number of cations required to neutralize the surface charge depends, of course, upon the number of excess anions in the alumino-silicate skeleton, and this property varies from one clay mineral to another. The number of cations required to neutralize the negative surface charge of a clay material is referred to as the "cation exchange capacity" of that material. It is generally expressed as milliequivalents (of charge) per 100 gm (of material). Some typical cation exchange capacities are given below.

Table 1. Cation exchange capacities of sediment minerals

| | |
|-----------------|-----------------|
| Quartz | 1-2 m.e./100 gm |
| Kaolinite | 3-10 " |
| Illite | 10-40 " |
| Montmorillonite | 80-150 " |
| Vermiculite | 100-200 " |

Ion exchange reactions may be expressed qualitatively as follows:



This means that a clay particle with adsorbed calcium ions changes to a particle with adsorbed sodium ions in the presence of a high concentration of dissolved sodium. Calcium ions are released to the solution. This transformation is an ion exchange reaction. It could be expressed quantitatively by means of a mass action relation where the concentrations are expressed in equivalents.

$$\frac{[\text{Na-Clay}] [\text{Ca}^{++}]}{[\text{Ca-Clay}] [\text{Na}^+]} = k$$

There are several alternative ways of expressing this quantitative relationship, but the basic trouble with each is that the thermodynamic concentration or chemical activity of what we have called "Na-Clay" and "Ca-Clay" has thus far proved indeterminable. The theoretical relationships, therefore, do not allow one to predict exactly what will take place when a mineral particle moves from the soil to the estuarine environment. In the present state of knowledge it is necessary to determine such relationships empirically.

At the same time, it is useful to consider what factors influence ion exchange reactions. This can be done best with reference to the mass action expression. The factor of first importance is the relative concentration of the various ions in solution. We have seen that qualitatively, in the presence of high relative sodium concentration, a sodium clay should form by ion exchange. Concentration is the driving force that allows the sodium ions to compete successfully for the negative exchange sites on the surface of the clay particle. As the relative concentration of an ion in solution decreases, its ability to compete successfully for the exchange sites also decreases. The proportion of exchange sites occupied by the ion should decrease. Sea water contains several important cations. Its composition on a milliequivalents per kilogram basis at a chlorinity of 19‰ is as follows:

Table 2. Concentration of major cations in sea water, 19‰ Cl⁻

| | m.e./kg |
|------------------|---------|
| Na ⁺ | 0.459 |
| Mg ⁺⁺ | 0.105 |
| Ca ⁺⁺ | 0.020 |
| K ⁺ | 0.010 |
| Sr ⁺⁺ | 0.0003 |

Even on an equivalent basis, therefore, sodium is the most important cation in sea water. Magnesium is the next most abundant, and calcium and potassium are relatively low in concentration. We might expect, on this basis, that sodium and magnesium exchange ions should predominate on marine sediments.

The second important factor is the relative concentration of positive charge possessed by the dissolved ion. The more highly concentrated is its positive charge, the more it can successfully compete

for the negative exchange sites. In terms of Coulombic forces this occurs because a small, highly charged ion can get closer to the source of negative charge than can a large ion of relatively low charge. We might expect, therefore, that the ions would be preferentially adsorbed in the inverse order of their relative sizes. A peculiarity of aqueous chemistry comes into play here, however. Ions in solution are hydrated, i.e., surrounded by a number of water molecules held very tightly as a "hydration sphere." The ion and its hydration sphere move through the solution and participate in exchange reactions as a unit. The sizes of hydrated and non-hydrated ions most abundant in sea water are given below.

Table 3. Ionic and hydration radii of common sea water cations

| Ion | Ionic radius | Hydrated radius |
|------------------|--------------|-----------------|
| Na ⁺ | 0.98 Å | 4 Å |
| Mg ⁺⁺ | 0.78 | 8 |
| Ca ⁺⁺ | 1.03 | 6 |
| K ⁺ | 1.33 | 3 |

For ions of like charge the hydration radius decreases with increasing ion size, but divalent ions are much more highly hydrated than monovalent (being smaller and highly charged, they attract water dipoles strongly) and consequently have high hydration radii. On this basis, we might expect potassium and calcium to be the most readily adsorbed sea water cations because in the hydrated form they have the most favorable ratio of radius to charge — 1:3 for each.

The third important factor is the total ionic strength of the solution, irrespective of the relative concentrations of the individual ions. In dilute solutions there is a tendency for monovalent cations to compete less successfully than divalent or trivalent ions for exchange sites. This factor reflects the change in chemical activity of the ions with dilution. Some empirical data illustrate the point very clearly (Wiklander, 1955). The table below shows the ratio of Ca⁺⁺:K⁺ adsorbed on three clays equilibrated with chloride solutions in which calcium and potassium are in equivalent concentration.

Table 4. Effect of solution concentration on ratio of adsorbed Ca:K (Wiklander, 1955)

| | Concentration of mixed chloride solution | | | |
|-----------------|--|--------|---------|----------|
| | 0.1 N | 0.01 N | 0.001 N | 0.0001 N |
| Kaolinite | -- | 1.8 | 5.0 | 11.1 |
| Illite | 1.10 | 3.4 | 8.1 | 12.3 |
| Montmorillonite | 1.47 | 10.0 | 22.1 | 38.8 |

The ratio is also influenced by the cation exchange capacities of the minerals. This dilution effect should be an extremely important one in determining the ion exchange properties of sediments in the estuarine

region, i.e., in the transition zone from fresh to marine salinities. We might expect on this basis that at very low salinities the divalent cations, Ca^{++} and Mg^{++} , should dominate the exchange sites, while at progressively higher salinities the monovalent Na^+ and K^+ ions should progressively replace them.

The final factor that we shall consider is one mentioned previously by Dr. Salomon. There appear to be specific interactions between certain ions and certain alumino-silicate clay mineral skeletons. These specific interactions arise because the size and shape of the negative exchange sites on one mineral fit very perfectly the size and shape of one kind of ion. Such is the relation between the exchange sites of illitic clay minerals and the potassium ion. Thus illite preferentially adsorbs potassium from salt solutions in which other ions may be the major constituents. In other cases, specific bonding or polarization effects between the clay surface and the exchanging ion may occur. Organic matter associated with the clay materials may influence certain ion exchange reactions through ion-organic complex formation. The specific ion interactions have to be worked out for each individual alumino-silicate lattice and each clay-organic association. There is no way of predicting their effects on ion exchange relationships in estuarine sediments.

From the preceding discussion of theoretical factors that influence sediment ion exchange reactions, one can understand that the final result in any single environment depends upon a variety of factors. The picture with respect to estuarine sediments is especially complicated because of the estuarine concentration gradient. It is necessary at present to determine empirically the ion exchange properties of estuarine sediments in a variety of natural environments. Basic observations already exist for soil materials and for a single marine sediment sample. Soil clay materials typically contain a large fraction of exchangeable calcium and the remaining negative exchange sites are balanced by dissociated hydrogen ions, which give rise to the acidic reaction characteristic of soils in humid climates.

Table 5. Exchangeable ions of a podzolic soil clay

| | |
|------------------|-----|
| H^+ | 82% |
| Ca^{++} | 10% |
| Mg^{++} | 5% |
| K^+ | 3% |

Such clay materials are referred to as calcium-hydrogen exchange materials. The meager data available suggest that marine clays may be predominantly magnesium-potassium exchange materials, but no modern determinations of exchange ions on marine sediments are available. It has generally been assumed that at sea water salinities magnesium and potassium must be preferentially adsorbed, partly as a result of specific interactions. Some understanding of the process by which terrestrial soil materials are adjusted to marine conditions during their transport through an estuarine system can be gained from the data given below.

Empirical observations: The ion exchange properties of sediments in

the Rappahannock River estuary, a tributary of Chesapeake Bay, have already been noted in abstract (Nelson, 1961) and will be described in full detail elsewhere. The Rappahannock possesses a salinity gradient of 0-20 ‰ spread out over a distance of about fifty miles. I have determined the ion exchange capacities and the exchangeable cations of the sediments throughout this estuary: along the gradient, in several transverse profiles, and to depths of three feet in cores obtained at each station. These determinations were carried out in the field by means of a mobile laboratory facility positioned on shore adjacent to the sampling site. Thus the data obtained represent, as closely as possible, the in situ conditions that exist in the sediment.

The cation exchange capacity of sediments in the Rappahannock estuary varies between 20-35 m.e./100 gm. This reflects the fact that the sediments consist predominantly of kaolinitic, vermiculitic, and illitic minerals with admixed silt-size quartz.

The exchange ion populations at different positions along the estuarine salinity gradient are shown graphically in Figure 2. In freshwater, calcium is the dominant exchange ion and the total of exchangeable ions is less than the exchange capacity. The balance consists of hydrogen ion. Such sediments possess an acidic reaction. In brackish water, sodium begins to occupy the exchange sites and, as the salinity increases in this zone, sodium replaces calcium as the dominant exchange ion. The total exchangeable ions equals the exchange capacity, indicating the acidic character of the sediment has been neutralized. (Figure 3 shows sediment pH variations that correspond to this trend.) In brackish water, the concentration of magnesium and potassium apparently is too low to have any effect on the exchange complex. In the more saline portions of the estuary, however, potassium and magnesium begin to make up an important fraction of the exchangeable cations. This appears to be related to the increasing ionic strength of the water. Near the mouth of the estuary, exchangeable potassium and magnesium are about equivalent to exchangeable calcium, while sodium is still the dominant ion.

The observed ion exchange properties of these sediments correspond in some ways with what we might have predicted from theory, but in some important respects they do not. The influence of concentration, for example, is reflected by the dominance of exchangeable sodium throughout the estuarine region. We do not, however, observe the expected effects due to sea water dilution. We would have predicted more important exchangeable calcium and magnesium at low salinities and an increase of sodium and potassium with increasing salinity. No exchangeable magnesium is detected in very brackish water, and the exchangeable calcium seems to be inherited from the soil materials supplying the estuary with sediment. Similarly, the effects of hydration character and ionic size and charge are not reflected in these data. We have not tried to evaluate the specific interactions between ions and mineral surfaces; the mineralogical composition of these sediments is too complex for a simple treatment. It is gratifying to discover some correspondence between observation and prediction, at least as far as the most important exchange reaction variable is concerned, i.e., relative ion concentration. Perhaps more detailed work will

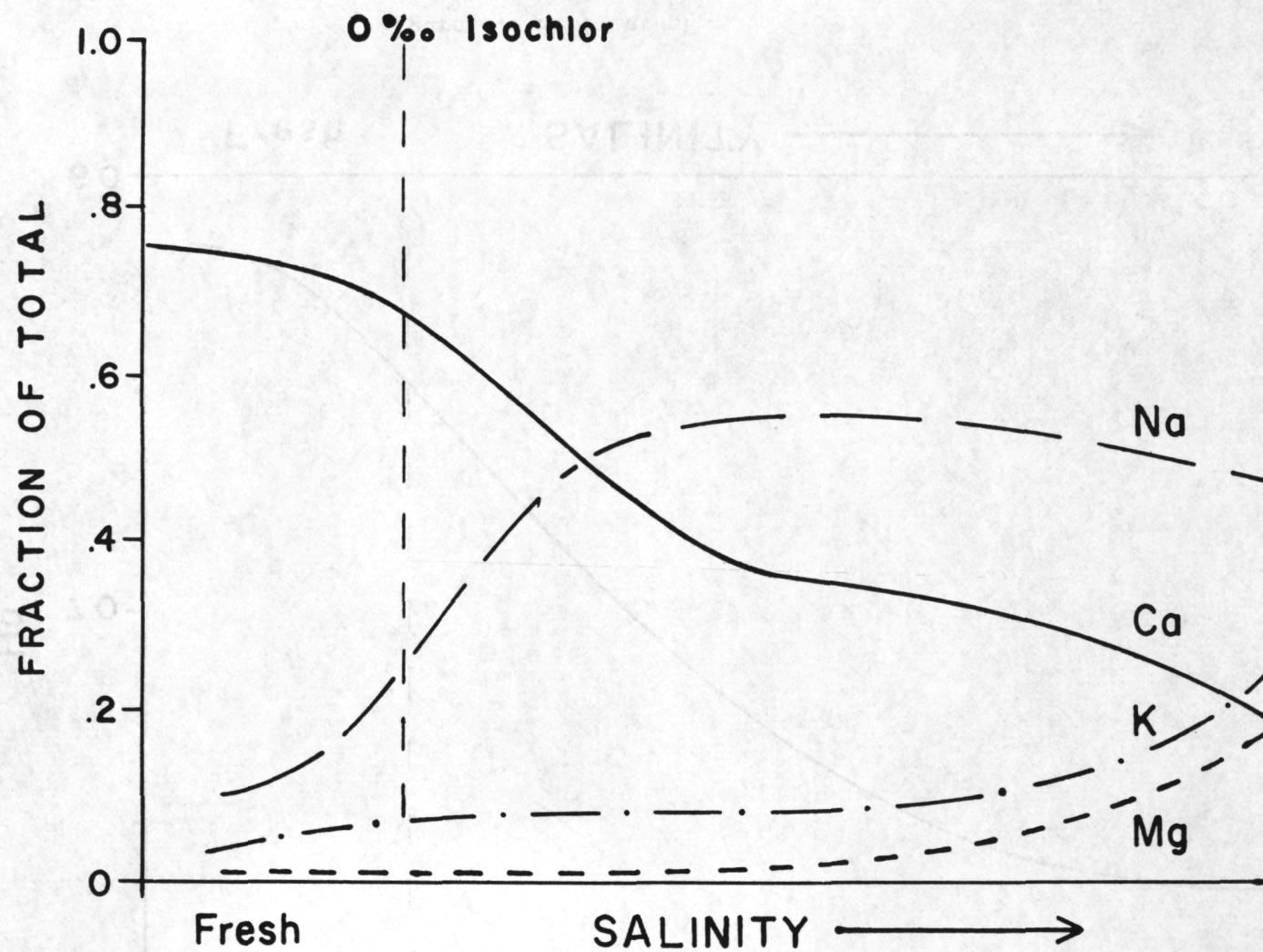


Figure 2. Sediment exchange cations.

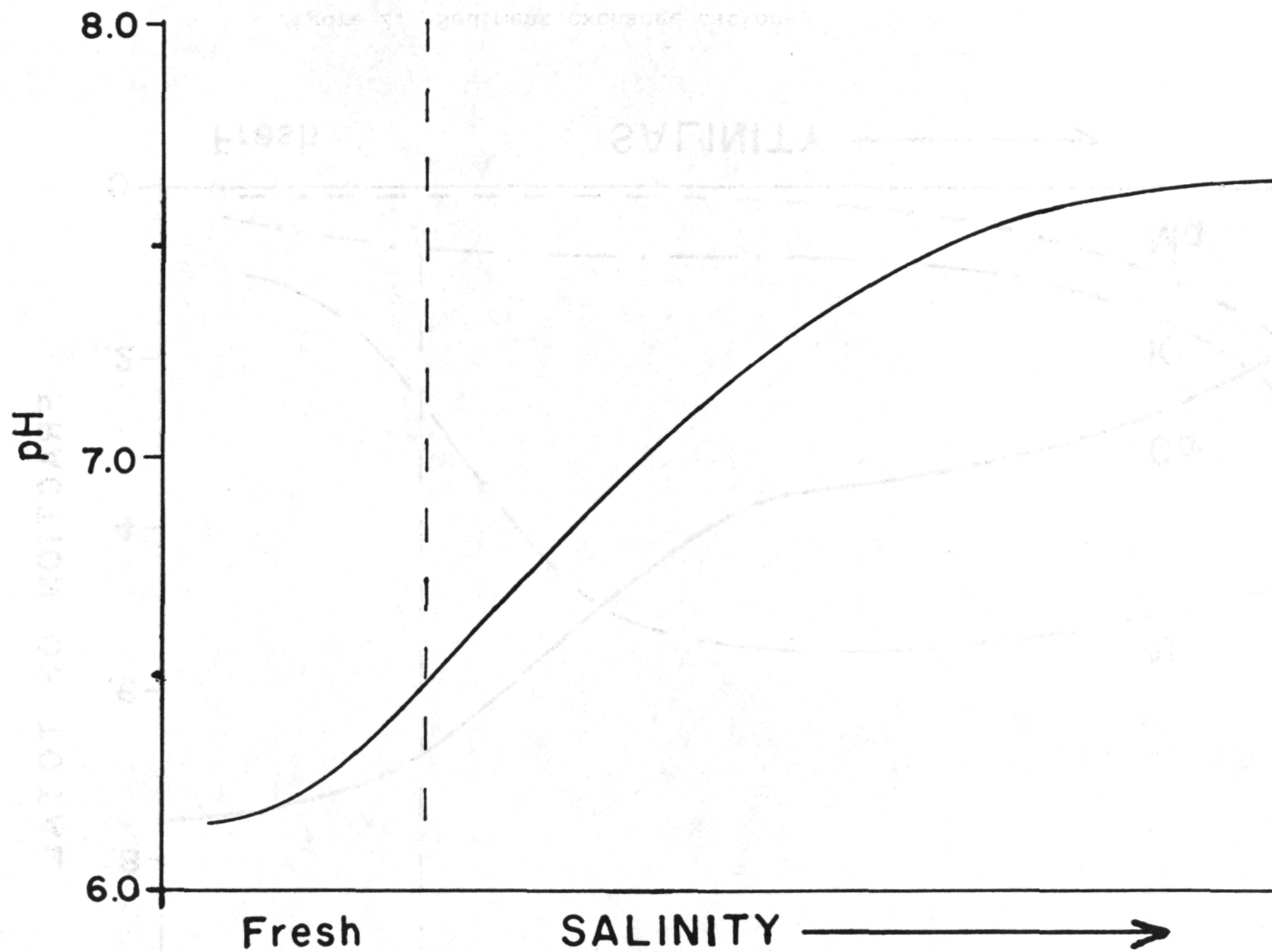


Figure 3. Sediment pH.

reveal other correlations as well. It would, of course, be interesting to follow the trends revealed by these data into the higher salinity region of a suitable estuarine system.

SEDIMENT AS A CHEMICAL COMPLEX

Perhaps the most important ecological effect of the sedimentary substrate is its role in maintaining unique chemical conditions at the bottom and in the water immediately adjacent. It has been possible so far only to make a crude beginning at understanding the factors that contribute to differences in chemical environment in an estuary. The chemical complex consists of several separate but interdependent parameters. They include texture and structure, organic fraction, pore water chemistry, ion exchange equilibria, gas equilibria, and microbiological activity. The in situ structure and texture of sediment is important because it establishes the framework within which chemical and biochemical processes work. While it is possible to measure the particle size distribution in a disaggregated sediment sample, no determinations of the in situ texture, porosity, or fabric of fine-grained estuarine sediments have been made. We have an even more rudimentary understanding of pore water chemistry and gaseous equilibria than of ion exchange reactions. The organic component serves as an energy source for microbial metabolism, as a modifier of inorganic chemical reactions through complex formation and chelation phenomena, and as a reacting system in its own right. Although suitable techniques have been developed for determining the total organic carbon in sediments, the forms in which it occurs remain a mystery. It is well known that micro-organisms are very active in the sedimentary substrate, but their true role in determining chemical aspects of the environment remains to be worked out. Undoubtedly, this is an extremely important aspect of sediment chemistry.

I have not begun to study all of the above parameters contributing to the chemistry of the sedimentary substrate, but I have measured water contents and certain aspects of the pore water chemistry: alkalinity, pH, chlorinity, and major ion composition. I have obtained preliminary estimates of the gaseous components: ammonia, hydrogen sulfide, and carbon dioxide. These studies, too, were made from a field laboratory. The basic trends in these parameters for typical sediment profiles and their aerial variations will be briefly noted below, but a detailed treatment will be given elsewhere.

The change in chemical character of estuarine sediments between freshwater and the sea is most generally reflected by the change in sediment pH which takes place along the estuarine salinity gradient. Figure 3 graphically illustrates the relations that have been found. Freshwater sediments are slightly acidic in reaction, just as are soil clay materials (soils may have pH's of 4.0). This is because the negative surface charges are not balanced by metallic cations in freshwater but rather by hydrogen ions whose dissociation gives rise to the acidic reaction. As the clay materials are moved progressively into more saline water, their pH rises until they become moderately alkaline in reaction. This results from saturation of the negative surface charges with basic cations. Curves similar to Figure 3 are obtained when an acid clay is titrated with a base or a neutral salt solution. Figure 3 thus

represents the titration or neutralization of freshwater clay material with sea water.

The vertical change in pH within an estuarine sediment profile (Figure 4) is determined first by the cation exchange status and then by gaseous equilibria in the sediment. In general, the pH increases slightly with depth, and at some horizon a short distance below the surface the pH passes through a maximum. The maximum and the depth increase correspond very closely with the trends of the ammonia distribution curve in Figure 4.

The water content of a muddy estuarine surface sediment normally is very high. At the surface, about 80% of the weight may be water. This means there is four times as much fluid as solid. Normally, the water content decreases regularly with depth (Figure 4), if constant texture is maintained, until the water content is about 50% at a depth of three feet. This means, of course, that the reacting system is becoming a progressively more condensed phase with depth. Ionic dissociation, biochemical processes, and gaseous equilibria should all be influenced by the decrease in fluid fraction, especially since the sedimentary particles comprising the solid fraction possess colloidal properties. The consequences have not yet been studied in detail.

The aqueous solution that fills interstitial spaces between the sedimentary particles in a sediment is called the pore water. The chlorinity of this pore water increases from the upper to the lower estuary in the same way that the overlying water increases in chlorinity. Normally, the chlorinity of the pore water at the sediment surface slightly exceeds that of the adjacent overlying water. The pore water chlorinity shows no systematic variation with depth in profiles from the upper brackish portion of the estuary, but in the lower saline parts of the estuary the pore water chlorinity increases with depth below the sediment surface. Likely, these two patterns of vertical variation are related to the nature of vertical diffusion processes that operate in sediments in different parts of estuaries. Within the pore water the ratios between major metallic cations and chloride ion have been found to be relatively constant throughout the estuarine region. The relative concentrations of the different cations remain about the same and, as far as present detection methods permit, it appears that the major cations are conservative elements in the sediment chemical system.

Pore water titration alkalinity varies systematically from one part of the estuarine region to another. It appears to be one of the most useful potential ecological parameters for detecting significant changes in the environment. At the sediment surface, the pore water alkalinity generally increases from fresh to saline water, just as does the alkalinity of the estuarine water itself. But, whereas the alkalinity of sea water seldom exceeds 2 m.e./l, pore water alkalinities commonly reach 5 or even 10 m.e./l. The alkalinity increases from well ventilated to poorly ventilated portions of the estuarine system. A pronounced increase in alkalinity takes place with depth in all sediment profiles (Figure 4). At depths of three feet below the surface in poorly ventilated basins, alkalinities of over 30 m.e./l have been

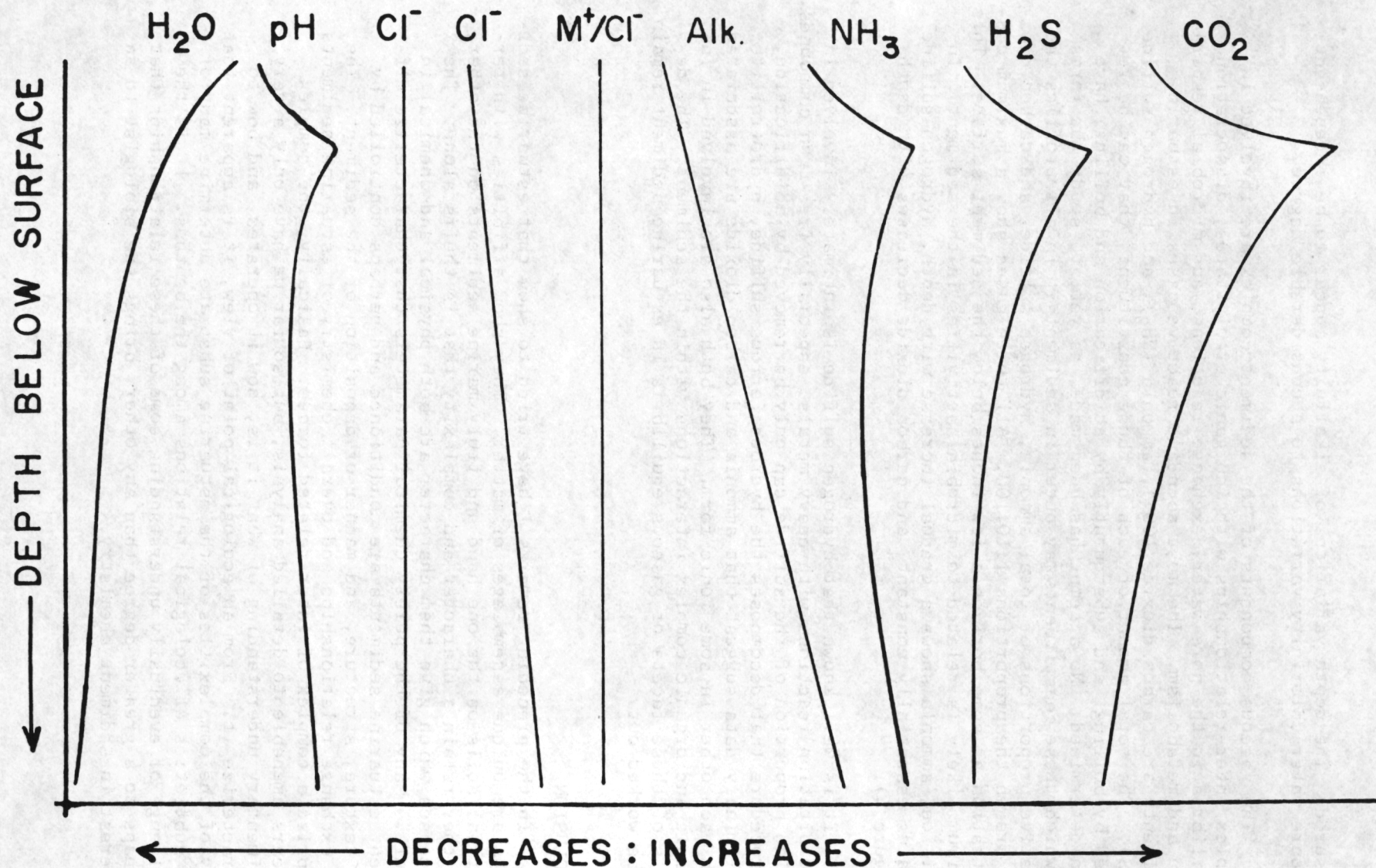


Figure 4. Sediment chemical parameters.

measured. The depth variations of alkalinity appear to be independent of pore water chlorinity variations to a considerable degree.

The gaseous components of the sediment complex are involved in complex inter-relationships with inorganic precipitates, dissociation equilibria in the pore water, exchange reactions, and microbial respiration and metabolism. The most abundant reactive gases in estuarine sediments are carbon dioxide (CO_2), ammonia (NH_3), and hydrogen sulfide (H_2S). The total amount of each of these constituents that can be removed by boiling, and subsequently by acidification and boiling, have been determined. No attempt has been made, as yet, to study the forms in which these constituents may occur in sediments. In all profiles the relative proportions of total ammonia, hydrogen sulfide, and carbon dioxide are in the proportions 1:10:100. All three gases show a maximum concentration at some horizon a few inches below the sediment surface. This maximum likely is related to microbial activities in the sediment. In addition, ammonia shows a gradual increase with depth, hydrogen sulfide remains essentially constant, and carbon dioxide decreases with depth (Figure 4).

It is well known that hydrogen sulfide is intimately involved in precipitation reactions with heavy metals, especially free iron compounds. A high proportion of the sulfide can only be removed by acidification, a procedure that decomposes the hydrous ferrous sulfide, hydrotroilite. Preliminary data suggest that ammonia and carbon dioxide are associated with each other in some ionic form. They both also are involved in inorganic and organic complex interactions within the sediment. The details of these facets of gaseous equilibria in estuarine sediment remain to be worked out.

CONCLUSION

In the preceding remarks I have tried to show that estuarine sediments are unique assemblages of matter. They show affinities with terrestrial soils on the one hand and truly marine sediments on the other, but they retain a character and complexity that is theirs alone. The processes which give them character are both physical and chemical in nature. Many of the purely chemical parameters that characterize different estuarine sediments are conditioned and perhaps controlled by the texture, structure, and manner of deposition of the sediment. The ion exchange relationships and overall chemistry of estuarine sediments comprise a complex of inter-related forces. Basically, the complex appears amenable to detailed analysis, but so far we have only a very rudimentary understanding of what it is, how it operates, and how to characterize it. From an ecological point of view, it is apparent that many of the complexities of the estuarine substrate determine many of the subtleties of ecological relations among the benthos. It is the challenge of eventually understanding some of these relationships that, perhaps to a greater degree than any other, brings the biologist to an interest in sediment chemistry.

DEPTH BELOW SURFACE

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SOME EXPERIMENTAL STUDIES WITH ORGANIC COMPOUNDS AND MINERALS*

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INTRODUCTION

A brief look into the literature will disclose a long bibliographic list of descriptive studies concerning organic material in sedimentary deposits and sea water. In the earlier years of investigation, the principal interest was in using organic content as a means of describing and thus classifying the sediments. We determined the organic carbon and the organic nitrogen content. We correlated organic carbon with inorganic particle size. We observed the general decrease of organic carbon with depth in the sediment. We applied dubious factors to convert organic carbon and nitrogen data to total organic material, thus losing the value of good analyses. We tended to compile data and produce average values, many of which had little meaning since divergent environmental situations were lumped together. We calculated C:N ratios and speculated as to their significance. Despite the shortcomings, all this was extremely valuable; it gave us the groundwork for the future and afforded some very important clues.

With the advent of more sophisticated analytical techniques, such as mass spectroscopy and chromatography, we were finally able to determine some of the individual organic compounds in both marine sediments and sea water. All those interested in this area of research are well aware of the excellent analytical results which have demonstrated the presence of hydrocarbons, carbohydrates, proteins, fatty acids, and many other organic compounds in marine sediments and sea water. Some selected references on investigations pertinent to organic materials in sediments and sea water are included at the end of this paper.

Our present analytical knowledge is far from adequate but at least we have some information. However, when we pose the question, "How does the organic material become a part of the sedimentary deposit?", we reach the end of our knowledge. By the use of logic, we can develop possible answers to this question. We know that in sea water sedimentary minerals are suspended temporarily in the water column. We also know that organic compounds are present in the water column and that they have but three routes to follow. They can be incorporated into the living organisms of the sea, be decomposed into their ultimate products, or find their way to the sediments of the bottom. Since we are interested in sediments let us confine ourselves to the latter possibility.

There are two basic ways for sea-borne organic material to become incorporated into the sediments, either by a settling out of the detrital

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