TRANSPORT OF SEDIMENTS BY WAVES,
ADRIATIC COASTAL SHELF, ITALY

BY

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ABSTRACT

Knowledge of marine-sediment transport in shallow water is as yet insufficient to give much help to the geologist who maps the distribution of ancient sandstone bodies. In order to improve this knowledge, the bottom sediments of the Adriatic Sea near the Italian coast were sampled and analyzed. These sediments were transported as uniform suspensions. A close relation was found between certain grain-size parameters, particularly the 1 percentile, and sea depth, indicating that turbulence induced by waves was a major factor in the sand distribution.

Another important factor that generally has been overlooked is percentage of sand in the sediment source for the area. If these source sediments contain little sand and consist almost entirely of silt and clay, the sand remains close to shore. If, however, sand is the predominant constituent of the source sediments, as commonly occurred in ancient seas, sand probably can be spread by waves across extensive areas as deep as wave base

The grain size of the sand also is an important factor in its distribution, some sand suspensions being displaced by gravity and some not. Therefore, grain size may determine the transport mechanism and, thus, the sediment distribution.

An understanding of these factors by the petroleum geologist is essential in his mapping and projection of sandstone deposits in the subsurface.

INTRODUCTION

Vertical and areal variations in the characteristics of sands are a controlling factor of sandstone reservoir characteristics. If the reservoir is a stratigraphic trap, petroleum accumulation is a result of these variations.

The economic significance of the characteristics of sand deposits induces petroleum geologists to investigate genesis and diagenesis of the sand. The present paper discusses a particular genesis: formation of sand deposits by waves.

In recent years considerable progress has been made in sedimentation research. The environment of deposition commonly, but not always, can be identified. The regional direction of currents in many cases is indicated by sedimentary structures. Unfortunately, little progress has been made in one fundamental field—that of sediment transport, to which the characteristics of sediments are closely related.

Among various modes of transport of sand, distribution by waves formed the largest volume of ancient marine sand deposits. Yet little is known about the action of waves on the sediments of an open shelf. Systematic observations supporting the opinions commonly expressed on the maximum depth of wave action are lacking.

Such fundamental information as the sediment content of bottom water during storms is not available. Even less is known about the direction of transport, down- or upslope, of sands of different grain size.

Studies of Recent and ancient sediments are mainly descriptions of sediments as they are found and observed. In order to obtain the fundamental information still lacking, there now is a need for field research on the dynamics of sedimentation.

The present paper is an investigation of the mechanism of sand distribution in a limited area of the Adriatic coastal shelf along the east coast of Italy. Movement of sand was not observed directly but was reconstructed to explain the present distribution. Texture was compared with the texture of other sediments to determine the transport mechanism. Information also was obtained by comparing the grain-size distribution in this area with similar distributions on shelves of other seas.

SAMPLING

Adriatic bottom sediments were sampled along the Italian coast in an area between the ports of Ortona and Pescara, from the 10- to the 50-meter isobaths. This area, shown on Figure 1, is 22 kilometers long and 10 kilometers wide.

Only the uppermost part of the sediments was sampled and it was assumed that this part was deposited since the sea attained its present level.

In view of the nearness of the shore and the close relation between certain sediment characteristics and sea depth, this assumption is justified.

Samples were taken from a trawler equipped with an echo meter while the trawler successively followed the 10-, 15-, 20-, 25-, 30-, 40-, and 50-meter isobaths.

Along each of these isobath lines, sampling stations were spaced at approximately 1,500-meter intervals. At each station two or three samples were taken. Sand was sampled with a grab sampler, and samples of homogeneous texture were selected for grain-size analyses. Muds were sampled with a short core barrel, but only the uppermost part of the core was analyzed. The total number of stations is 106 and the total number of samples 267.

The samples were treated by hydrogen peroxide in order to destroy the organic matter without acid treatment. The fraction coarser than 31 microns was analyzed with sieves. The finer fraction was dispersed with pyrophosphate and analyzed with pipette.[4]

The grain-size analyses of the samples taken along each isobath were represented by a *CM* pattern. An attempt was made to reconstruct the sedimentation by using these patterns.

BRIEF REVIEW OF MARINE SEDIMENT TRANSPORT

The purpose of this work is to give a better understanding of sediment distribution by marine agents. Reliable information supplied by the study of present oceans is available only for certain environments.

Longshore currents, fairly well known, can transport sand and pebbles for distances of more than 100 kilometers along the shore in a narrow belt only a few dozen meters wide.

Tidal currents may be swift in areas where tides are restricted by the topography. Transport by these currents was studied in tidal channels and over shallow banks. Sand waves moving at present on the continental shelf off the south and east coasts of England have been attributed to tidal action. The transport mechanism, however, is not well understood.

Something is known about turbidity currents which transport sand and a few pebbles to the

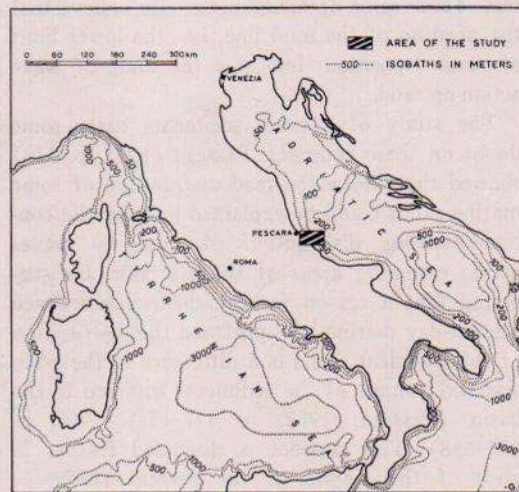[4] Analyses were made in the Geochemical Laboratories of AGIP, Direzione Mineraria.

Fig. 1.—Map of Adriatic Sea, showing area of study.

deepest parts of the oceans, but the mechanism that triggers these currents generally is still a matter for speculation. In certain areas, however, as at the mouth of the Congo River, it is probable that dense sand suspensions transported by rivers during floods can overcome the density difference between salt and fresh water and flow as turbidity currents into submarine canyons.

Waves are the transport agent that moved the largest volume of ancient sands. Waves act on relatively shallow bottoms on which the orbital motion, flattened by action of the bottom, creates an alternate to-and-fro current.

Numerous laboratory experiments and theoretical studies have been made to explain the action of waves on bottom sediments. The movement of natural or artificial sediments also has been traced on nearshore ocean bottoms. As yet this work has not led to the formulation of well-established laws controlling sediment motion.

It generally is accepted that shallowing waves induce a shoreward bottom current that tends to keep sand near the shore. This current probably is compensated for a certain distance above bottom by a seaward counter-current, or laterally by rip currents.

At times, a seaward bottom counter-current may be induced by the wind blowing the surface water onshore.

Some oceanographers still believe that sand can not be transported by waves for considerable distances from shore, or much deeper than 30 me-

ters. These same oceanographers also believe that the position of the mud line, *i.e.*, the lower limit of sand deposition, indicates the limit of wave action on sand.

The study of ancient sediments casts some doubt on these concepts. Passega (1962, p. 118) showed that the widespread distribution of some marine sands could be explained only by the contemporaneous distribution of sand by waves across extensive areas of the sea floor. He suggested that a reason for the difference between present-day marine transport and the distribution of these ancient sands is a difference in the grain size and volume of the sediments supplied to the basin (Passega, 1962, p. 117–118; 1964, p. 837–838). This concept is discussed further in view of the results of the present study.

Ideas about the limit of wave action gradually are changing. Recently silt suspensions by waves were observed by Moore (1963) at a depth of 100 meters.

In order to examine the relations between wave action and sediment distribution, median grain size and depth of bottom sediments sampled along profiles of several coastal shelves are plotted on Figure 2. With the exception of the Adriatic profile (I), these profiles were constructed from published data. For stations where several samples had been taken, the median shown on Figure 2 is the largest median.

Profiles II, III, and IV are on the southern California shelf near La Jolla (Inman, 1953, 1957). Another California shelf, discussed by Trask (1955), is represented by profile V. Profiles VI and VII are situated on the shelf of the Rhône delta, discussed by Kruit (1955).

Figure 2 shows clearly that, in the same area and at the same depth, the bottom sediment texture differs greatly. Medians of profile II are twice as great as those of profiles III and IV. Between profiles VI and VII, the difference is even larger. It is evident that if one profile reflects wave competency, the other profiles of the same area do not, and therefore are controlled by other factors. These factors are discussed in later paragraphs.
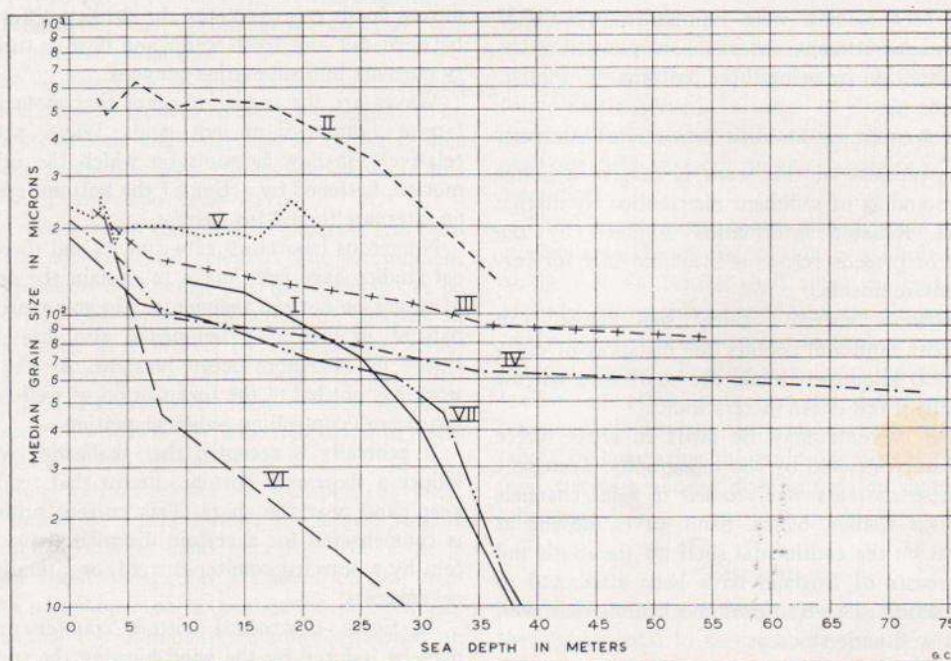

FIG. 2.—Profiles of a few nearshore shelves, showing variations of median grain size of bottom sediments with sea depth. I, Adriatic area of the study; II, La Jolla, California; III, Scripps Oceanographic Institution, California (Range D); IV, Scripps Oceanographic Institution, California (Range U); V, Point Conception, California; VI, Grand Rhône (mouth of Rhône River), France: VII, South Beauduc (Rhône delta), France.
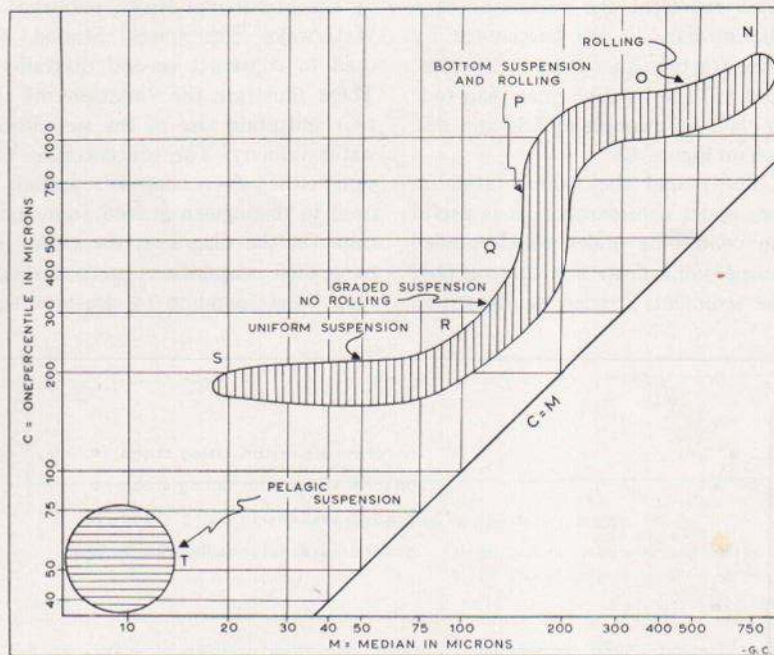
Fig. 3.—Typical *CM* diagram, from Passega (1964).

While gravel, sand, and part of the slit are transported on or near bottom by waves and currents, finer sediments form pelagic suspensions that can be transported by currents that do not reach the bottom and are deposited as mud. Pelagic suspensions may be formed either by discrete particles or by aggregates, such as those formed by flocculated clays. Grain-size analyses were made of the muds that form the bottom of the northern Tyrrhenian Sea. These muds were sampled at depths ranging from 40 to 1,500 meters (Fierro and Passega, 1965). Independently of the depth, all samples have almost the same grain-size distribution. The median diameter is 2–3 microns and the 1 percentile (approximate value of the maximum grain size) is less than 40 microns. Grains larger than 40 microns apparently can not be transported long distances as pelagic suspensions, and must be transported by bottom currents.

GRAIN-SIZE PARAMETERS

Two parameters were used to represent the coarsest part of the samples: C, the 1 percentile of the grain-size distribution which is an approximate value of the maximum grain size, and M, the median. Samples are represented by points forming a *CM* pattern. Characteristics of these patterns were discussed by Passega in two papers (1957, 1964).

Figure 3 shows the most general shape which a *CM* pattern can assume. It should be recalled that the different segments into which the pattern is subdivided by letters on Figure 3 correspond to different transport mechanisms. *NO* represents sediments transported only by rolling, *OP* sediments transported in part by rolling and in part in suspension, *PQ* sediments transported mostly in suspension but including a few grains that are rolled, *QR* sediments transported as a graded suspension, and *RS* sediments transported as a uniform suspension. The graded suspension is a bottom suspension characterized by upward-decreasing concentration and grain size. In the uniform suspension which generally overlies the graded suspension, concentration and grain size are relatively constant.

The part T of the diagram is formed by sediments transported as a pelagic suspension.

The *CM* diagram of a deposit can form the complete pattern of Figure 3 only if sediments of all sizes are available.

Other diagrams can be used to represent the fine fraction of the sediments of a deposit. *LM*

and *AM* patterns represent the variations as a function of the median of the percentage by weight of (1) the fraction finer than 31 microns, *L*, the lutite; and (2) the fraction finer than four microns, *A*, the clay. An example of *LM* and *AM* patterns is shown on Figure 12.

In order to understand the sedimentation in the Adriatic area under consideration, it is useful to examine the conditions under which graded and uniform suspensions flow. For this purpose the data on the sediments carried in suspension

by the Mississippi River, published by the U. S. Waterways Experiment Station (1939), were used to construct several diagrams (Figs. 4–6). These illustrate the variations of the concentration and grain size of the suspension and of the water velocity. The concentration of the suspension, either decreasing or constant upward, was used to distinguish graded from uniform suspension. On the diagrams, the points corresponding to graded suspensions were distinguished from those corresponding to uniform suspensions.
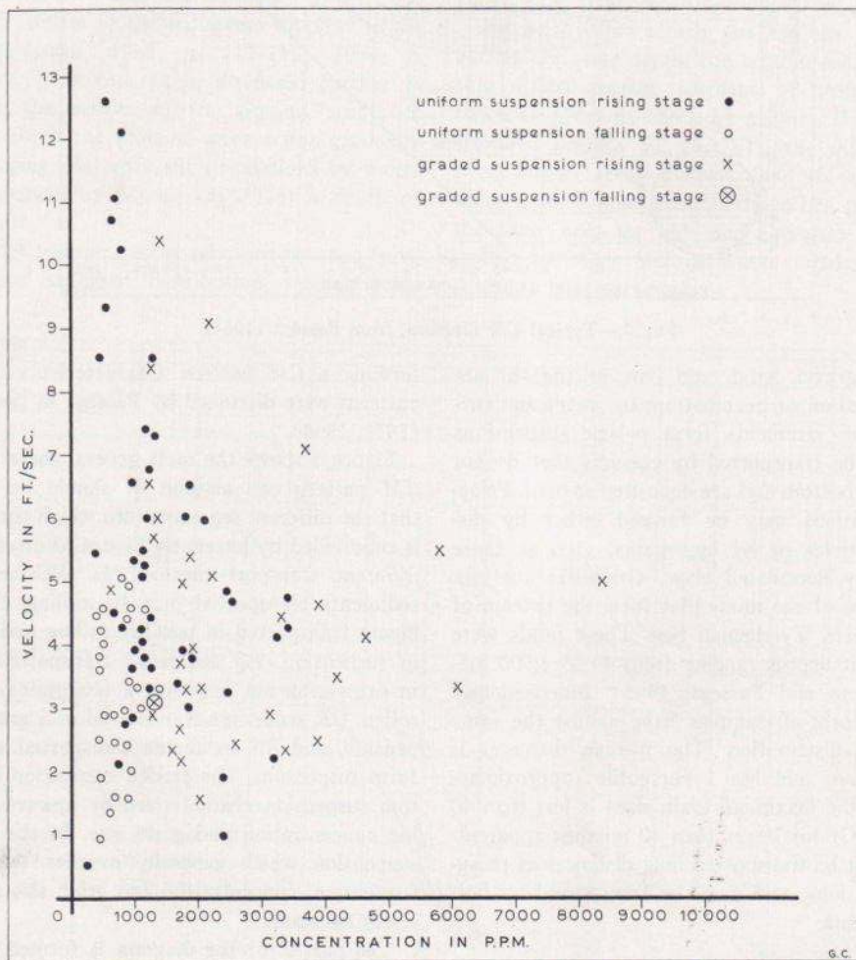

FIG. 4.—Velocity-concentration diagram, Mississippi River near Mayersville, Mississippi. Samples are taken at several stations in a section of river at various times. Each point of diagram represents series of samples taken at one station but at different depths during an observation. Concentration and velocity are average concentration and velocity of uniform suspension and of graded suspension, considered separately, for each station during an observation. Rising and falling stages of river are represented by different symbols.
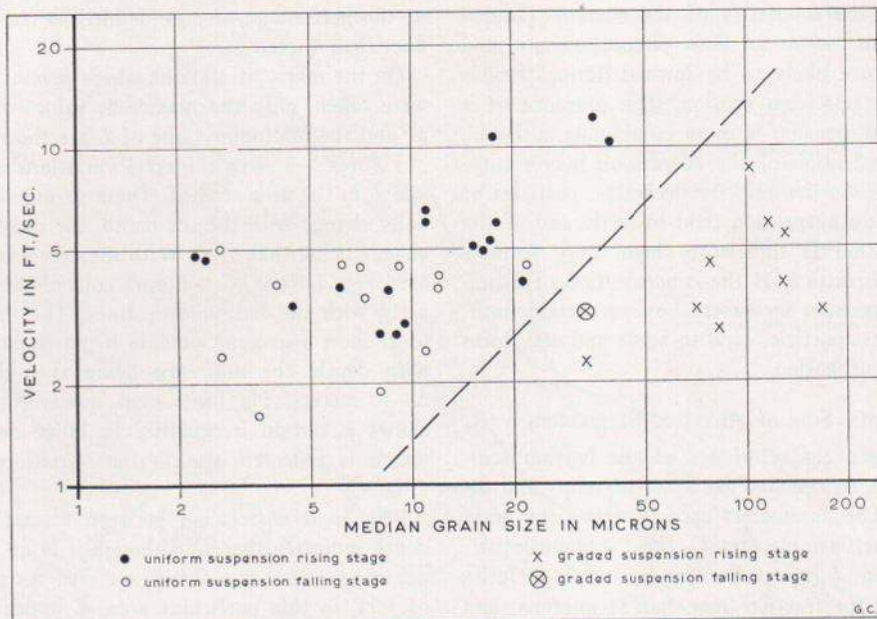
FIG. 5.—Velocity-median grain-size diagram, Mississippi River near Mayersville, Mississippi. Values are averages for graded and uniform suspensions at each station obtained as indicated in explanation of Figure 4..

The sediments represented on the diagrams, all sampled in suspension, were distinguished according to whether they were sampled during rising or falling stages of the river. The crest stage, during which a few samples were taken, was considered to be a part of the rising stage.

The first diagram (Fig. 4) represents the variations of the concentration of the sediment in suspension as a function of the water velocity. The diagram shows that uniform suspension is present both during rising and falling stages of the river, whereas graded suspension generally is present only during rising stages. Graded suspension can form at any water velocity greater than 2 feet per second. Graded suspension concentrations range from 1,000 to 8,500 ppm. Uniform suspension concentrations are highest during rising stages, but do not exceed 3,500 ppm.

The diagram of Figure 5 shows the variations of the median grain size of the suspended sediment as a function of the water velocity. As the velocity increases, the finest particles of the graded suspension pass into uniform suspension. The maximum grain size which can be transported in the graded suspension is a function of turbulence and therefore of current velocity (Passega,

1957). It can therefore be stated that, as velocity increases, some rolled grains pass into the graded suspension while some graded suspension particles are lifted into the uniform suspension.

This concept has been mentioned in different terms. Sundborg (1956, p. 218) discussed the passage of sediment from "bed load" to "suspended load" with increasing velocity. However, the terms "bed load" and "suspended load" are vague, graded suspension being considered at times as part of the bed load, and at other times as part of the suspended load. It is preferable to subdivide the load into rolled load, graded suspension, and uniform suspension.

Figure 6 shows the variations of the suspended sediment's median as a function of the concentration. This figure is particularly interesting because it shows that, if the concentration of the suspended matter exceeds 1,000 ppm., the coarsest particles of the uniform suspension pass into the graded suspension.

From these remarks some characteristics of sediment suspensions can be inferred. A bottom current transports sediments as a graded suspension where particles of appropriate size range are available. This range differs to a certain extent

with the characteristics of the current. Graded suspensions seem to flow discontinuously and probably are likely to be formed during periods of strong upstream erosion. The presence of a uniform suspension is more continuous, although the concentration of the suspension may change with time. As the velocity decreases, particles of the uniform suspension tend to settle and, if the concentration is sufficiently high, may form a graded suspension. If the concentration of a uniform suspension increases above a certain limit, the coarsest particles tend to settle and may form a graded suspension.

GRAIN SIZE OF ADRIATIC SEDIMENTS

Grain-size characteristics of the bottom sediments are represented on a set of maps and diagrams. The parameters used to define the grain size of each sample are: C, the 1 percentile; M, the median; L, the percentage by weight of lutite defined as the fraction finer than 31 microns; and A, the percentage of clay defined as the fraction finer than 4 microns.

On the maps, at stations where several samples were taken, only the maximum values of C and M and the minimum value of L are shown.

Figures 7–9 show the areal variations of C, M, and L in the area studied. These parameters gradually change with the sea depth, the most regular change being that of C. With the exception of the area near Ortona, C contours coincide almost exactly with the bathymetric lines. The variations of L show a general increase in lutite percentage with depth, the mud line being at a depth of 30–40 meters. The lutite map, however (Fig. 9), shows a certain irregularity in lutite deposition which is reflected also in the variations of M (Fig. 8).

The good correlation between C and bottom depth indicates that C, although it is an extreme parameter, also is a significant one. As a matter of fact, in this particular area, C appears to be
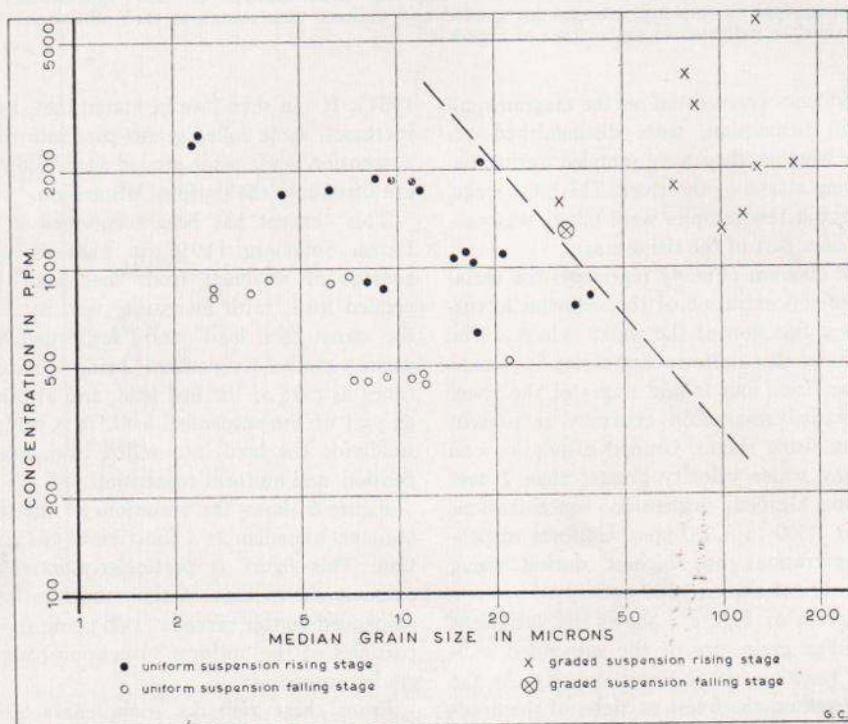

FIG. 6.—Concentration-median grain-size diagram, Mississippi River near Mayersville, Mississippi. Values are averages for graded and uniform suspension at each station obtained as indicated in explanation of Figure 4.
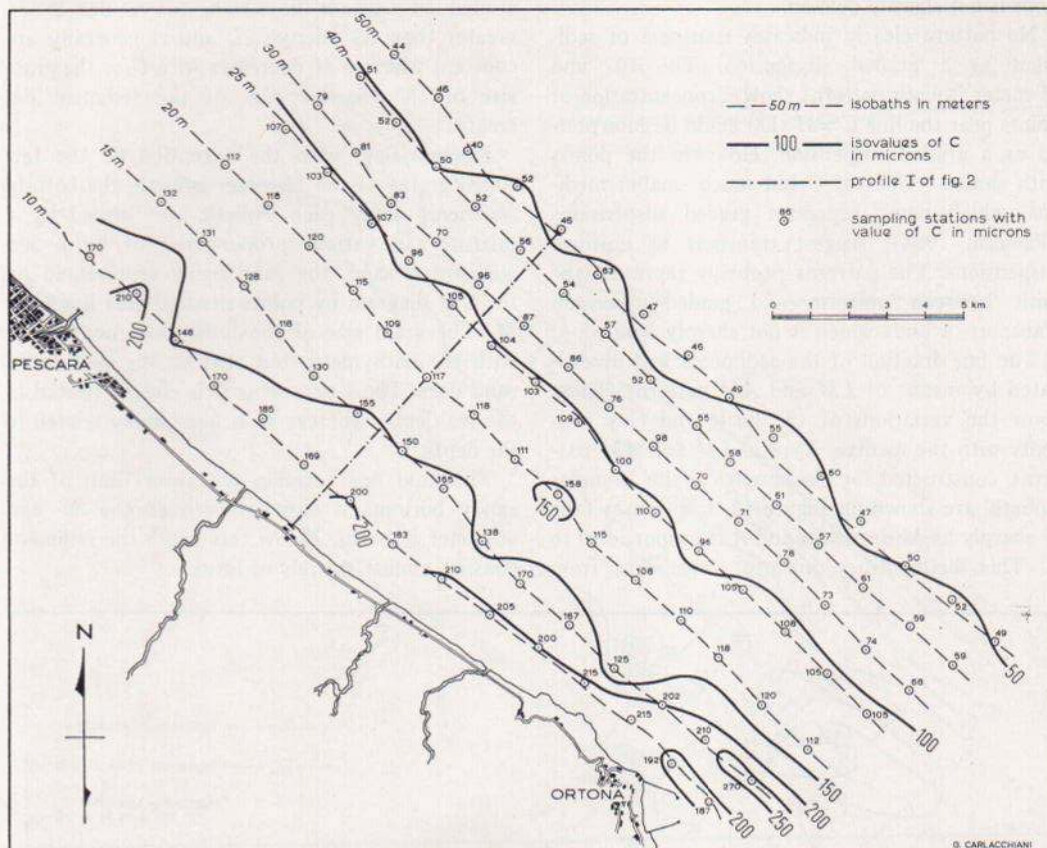
FIG. 7.—Areal distribution of C (approximate maximum grain size of bottom sediment) in area of study.

less sensitive to sampling errors than M. This supports the contention of the senior writer (Passèga, 1957) that the good correlation, not affected by sampling errors, between C and M which is characteristic of certain modes of transport, justifies the use of C for characterizing a deposit.

In the area of the study, grain size of lutite is constant and independent of the percentage of lutite in the sample as a whole. This is illustrated by Figure 10 on which the percentage by weight of clay in each sample (A) is plotted against the percentage of silt finer than 31 microns (L-A). It is clear that A is approximately proportional to L-A.

Several CM diagrams (Fig. 11 A, B, and Fig. 11 C, D, E, F, G) were constructed by grouping on each diagram the points representing all samples taken along the same bathymetric line. As can be seen, the CM patterns show little scatter.

CM patterns of the 10-, 20-, 25-, and 30-meter isobaths are uniform suspension patterns. On the 15-meter pattern, a few points have C values ranging from 200 microns to 5 millimeters and are scattered. These large grains are an artificial sediment resulting from dismantling by waves of concrete constructions built during the First World War. The coarse grains are rolled on a sand probably transported as a uniform suspension. These coarse grains are interesting because they behave like pebbles eroded by waves from a rocky coast.

The patterns of the 40-, and 50-meter isobaths may be considered to be patterns formed by pelagic suspensions. The absence of sand in the sediments indicates that sand can not be transported a certain distance by currents having no contact with the bottom. It must be noted, however, that the limit between uniform and pelagic suspen-

sions is not sharply defined.

No pattern clearly indicates transport of sediment as a graded suspension. The 10- and 15-meter isobath patterns show a concentration of points near the line $C = M$ that could be interpreted as a graded suspension. However the points with similar values of C but much smaller medians, which never represent graded suspensions (Passega, 1964), suggest transport as uniform suspensions. The patterns probably represent the limit between uniform and graded-suspension transport, a limit which is not sharply defined.

The fine fraction of the sediments was investigated by means of LM and AM patterns. These show the variations of the lutite and clay contents with the median. Typical LM and AM patterns, constructed for the samples of the 20-meter isobath, are shown on Figure 12. L increases fairly sharply as M decreases and A is proportional to L. This distinguishes uniform suspensions from

graded suspensions in which, for values of M greater than 80 microns, L and A generally are constant whereas M decreases with C as the grain size of the coarsest part of the sediment decreases.

Summarizing, with the exception of the few rolled grains of the 15-meter isobath, the bottom sediments along each isobath are formed by a mixture (in various proportions) of lutite and well-sorted sand, the sand being represented on the CM diagram by points situated near line $C = M$. The grain size of the lutite does not change with the bathymetry but that of the well-sorted sand does. The 1-percentile C is closely related to the sea depth, whereas M is less closely related to the depth.

The mud line forming the lower limit of the sandy bottoms is situated between the 30- and 40-meter isobaths. Below this depth the sediment consists almost entirely of lutite.
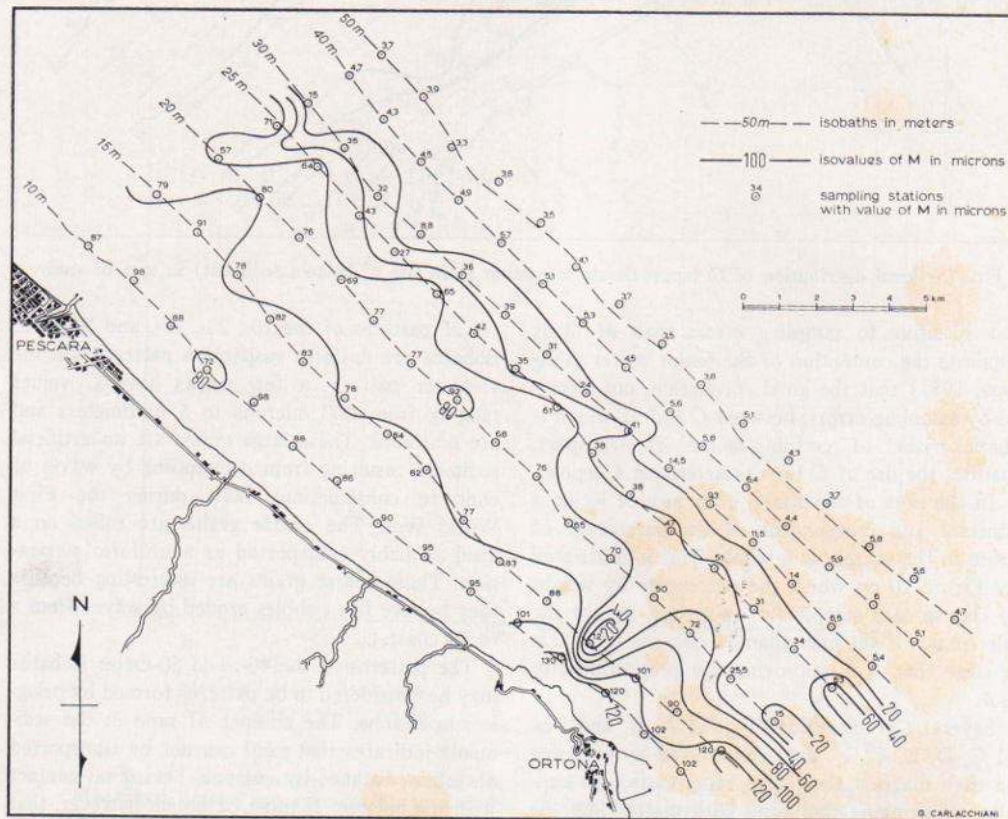

Fig. 8.—Areal distribution of M (median grain size of bottom sediment) in area of study.
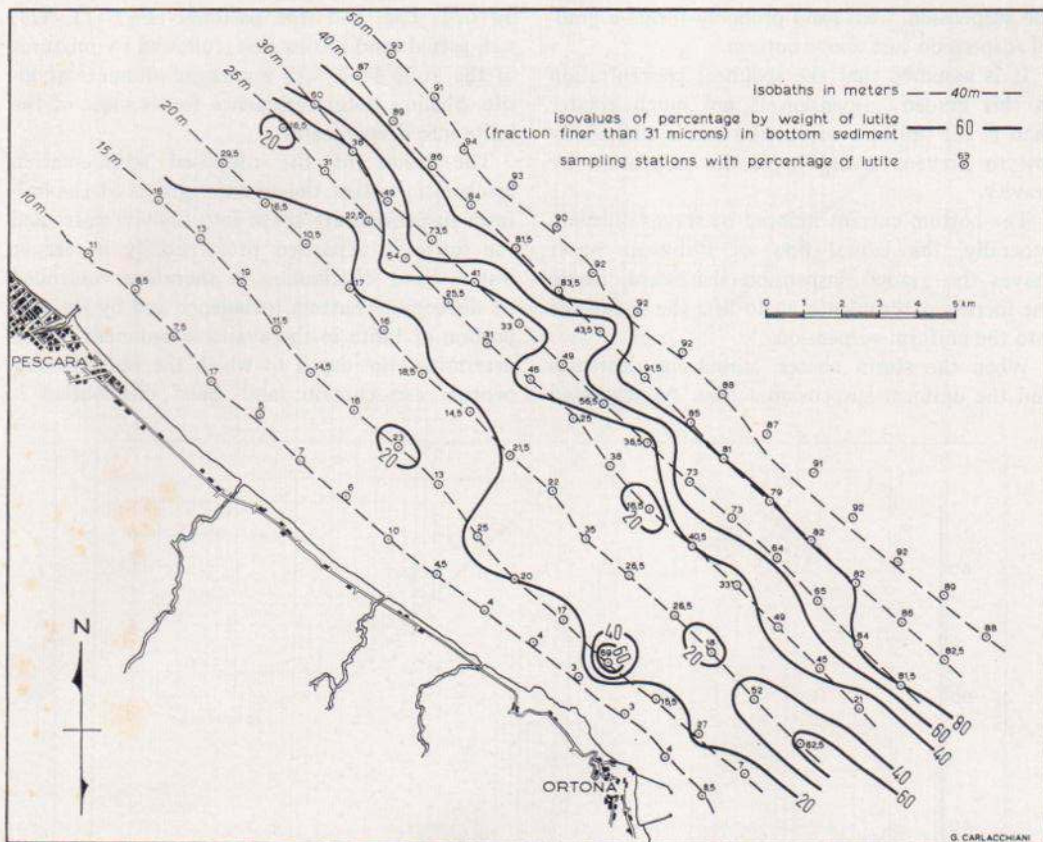
FIG. 9.—Areal distribution of L, percentage by weight of lutite in bottom sediment in area of study.

DISCUSSION OF WAVE SEDIMENTATION ON ADRIATIC COASTAL SHELF

Textural information suggests the following reconstruction of the sedimentation.

CM patterns of Figure 11 show that graded-suspension deposits generally are absent. This, as mentioned earlier, is caused by the deficiency in the area of sediments of appropriate grain size. Sand is fine and forms uniform suspensions. Silt and clay are transported either in uniform or in pelagic suspensions. A few coarse grains resulting from erosion by waves of a concrete construction are rolled as indicated by Figure 11-B.

The regular areal variation with sea depth of texture parameters, and particularly of *C*, illustrated by Figures 7–9, indicates the absence of local currents, such as rip currents, capable of transporting sediments seaward. Variations of the texture with depth can be attributed only to lat-

eral variations in the bottom turbulence induced by waves.

The first explanation that comes to mind for the maximum grain-size distribution is that at each place are deposited the largest grains that wave turbulence can lift. The mud line therefore would mark the lower limit of action of this turbulence on bottom sand. This explanation, however, is not in agreement with the indications of the profiles of Figure 2 or with the recent observations of wave transport, discussed previously. Another explanation is therefore suggested.

During a storm, in shallow water, waves could erode the sea floor deeply, if this action were not limited by the maximum concentration of sediments that waves can hold in suspension. As was mentioned in a preceding paragraph, in a uniform suspension, if lutite concentration increases above a certain limit, the coarsest sand is forced out of

the suspension. This sand probably forms a graded suspension just above bottom.

It is assumed that the sediment concentration in this graded suspension is not much greater than in the uniform suspension and is sufficiently low to prevent transport of the suspension by gravity.

The bottom current induced by waves or, more generally, the lateral flow of turbulent water moves the graded suspension shoreward, where the increased turbulence again lifts the sediments into the uniform suspension.

When the storm abates, turbulence decreases and the uniform suspension settles. As suggested

by *CM, LM,* and *AM* patterns (Figs. 11, 12), well-sorted sand settles first, followed by mixtures of the same sand with increasing amounts of lutite. Shallow-water turbulence forces most of the lutite into deeper water.

The result of the proposed sedimentation mechanism is that the coarsest grains of the uniform suspension are swept into shallow water and the lutite is deposited preferentially in deeper water. Sand distribution is therefore controlled by differential bottom turbulence and by the proportion of lutite in the available sediment, which determines the depth to which the uniform suspension can contain sand. Sand distribution is
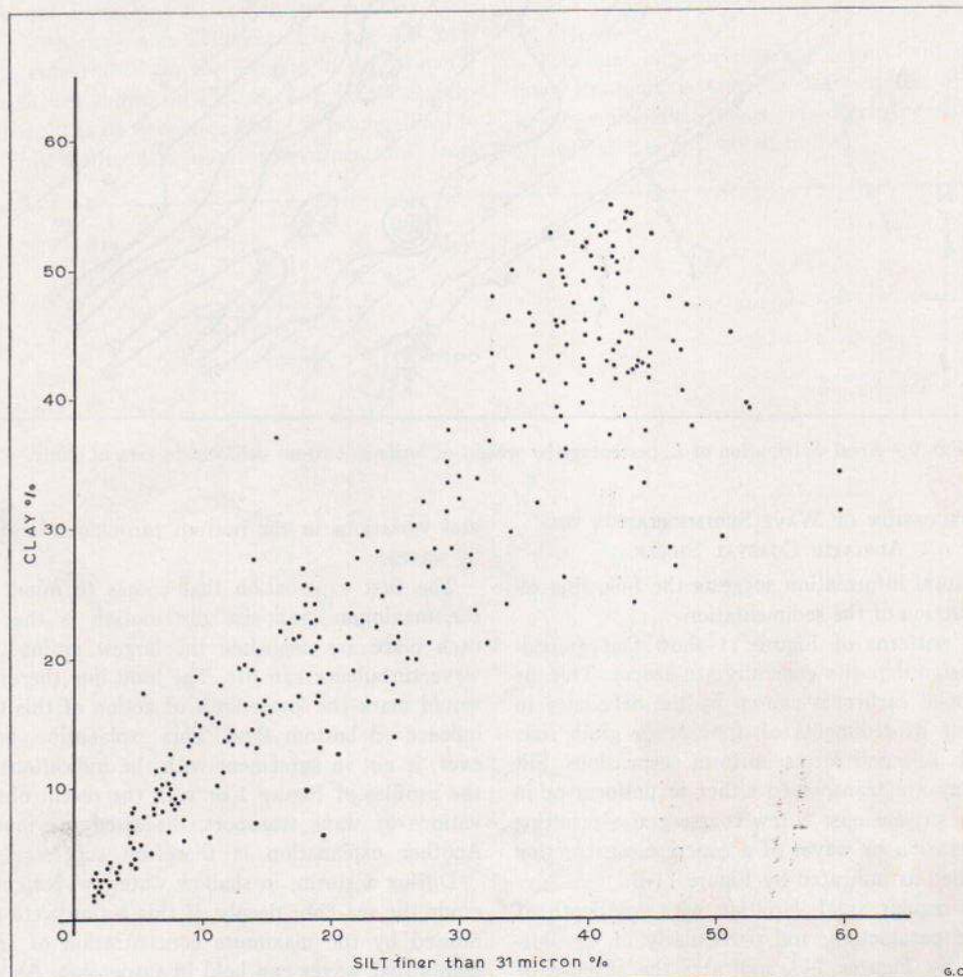

Fig. 10.—Clay-silt diagram showing for each bottom sample percentage by weight of clay (fraction finer than 4 microns) plotted against percentage of silt finer than 31 microns (fraction between 31 and 4 microns).
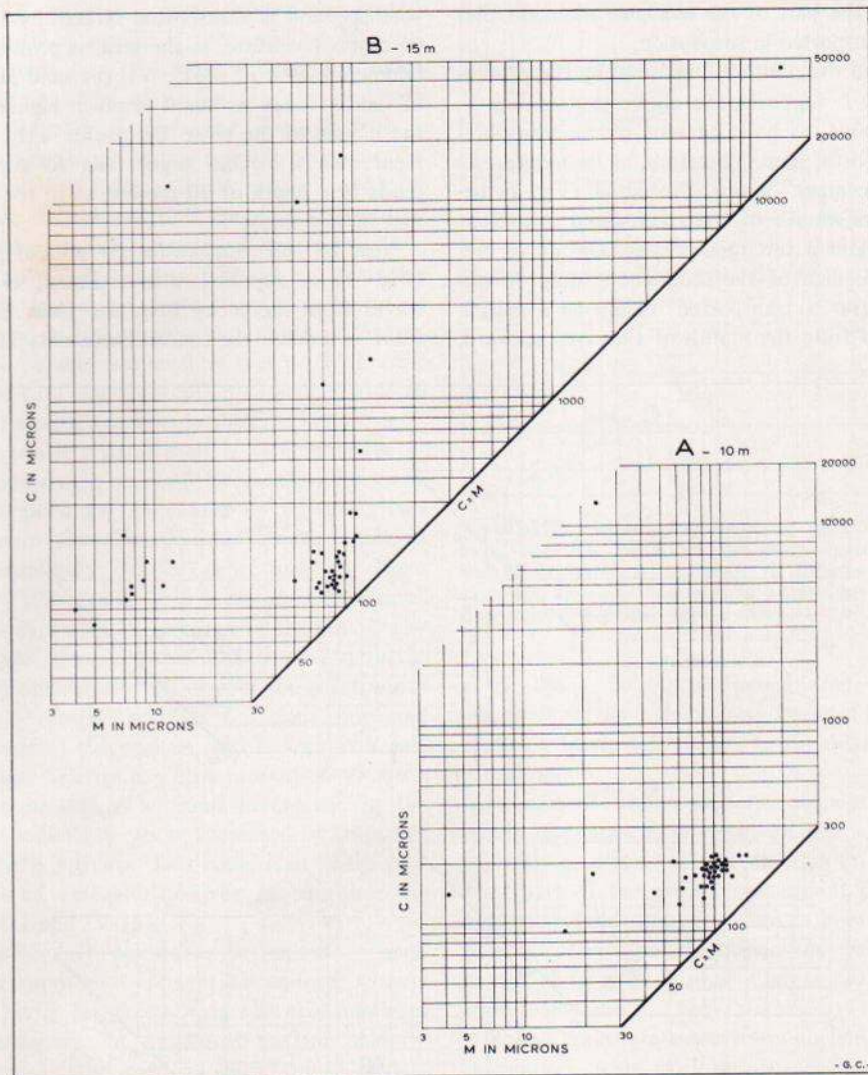
Fig. 11 A, B.—*CM* patterns. Patterns represent samples taken along following isobaths:
A.—10 m.; B.—15 m.

controlled by the maximum turbulence only if lutite is absent. Then bottom sand probably extends to wave base, which presumably is considerably deeper than 30 meters. In the extreme opposite condition, where the sediment as a whole is lutite, the entire sea floor and even the beaches are covered by lutite.

Between two storms, the lutite which is transported as a pelagic suspension settles.

As lutite is deposited, it becomes mixed with some of the bottom sand and forms a sediment having a low median and a value of C corresponding to the bottom depth.

The proportion of lutite in the bottom sediment changes somewhat along an isobath as indicated by Figure 9. This explains why C is more closely related to the sea depth than M. C therefore gives a good indication of the relative values of the sea depth. These indications differ from one area to another because they are dependent on the grain size of the available sediment, which may be expressed as the "sand percentage" by

weight in the part of the available sediment that can be transported in suspension.

The sand distribution illustrated by the profiles of Figure 2 supports the above explanation.

The Rhône, as most present rivers, transports relatively little sand. Therefore, at its mouth, the "sand percentage" is low. Profile VI (Fig. 2) begins at the mouth of the river. Sand is present only in water a few meters deep, and at 13 meters the median of the sediment is only 30 microns. Lutite is transported mainly as a pelagic suspension from the mouth of the river seaward,

whereas sand is transported largely by longshore currents. Therefore, in the area of profile VII, 20 kilometers west of profile VI, the sand percentage in the available sediment is much higher than at the mouth of the river. On profile VII, the sediment with a median larger than 30 microns extends to a depth of 30 meters, as in the Adriatic area of this study.

Near La Jolla, California, the area of profile II (Fig. 2) is supplied with sediment eroded by waves from the rocky Point La Jolla. This sediment is moderately coarse. Sediments of profiles
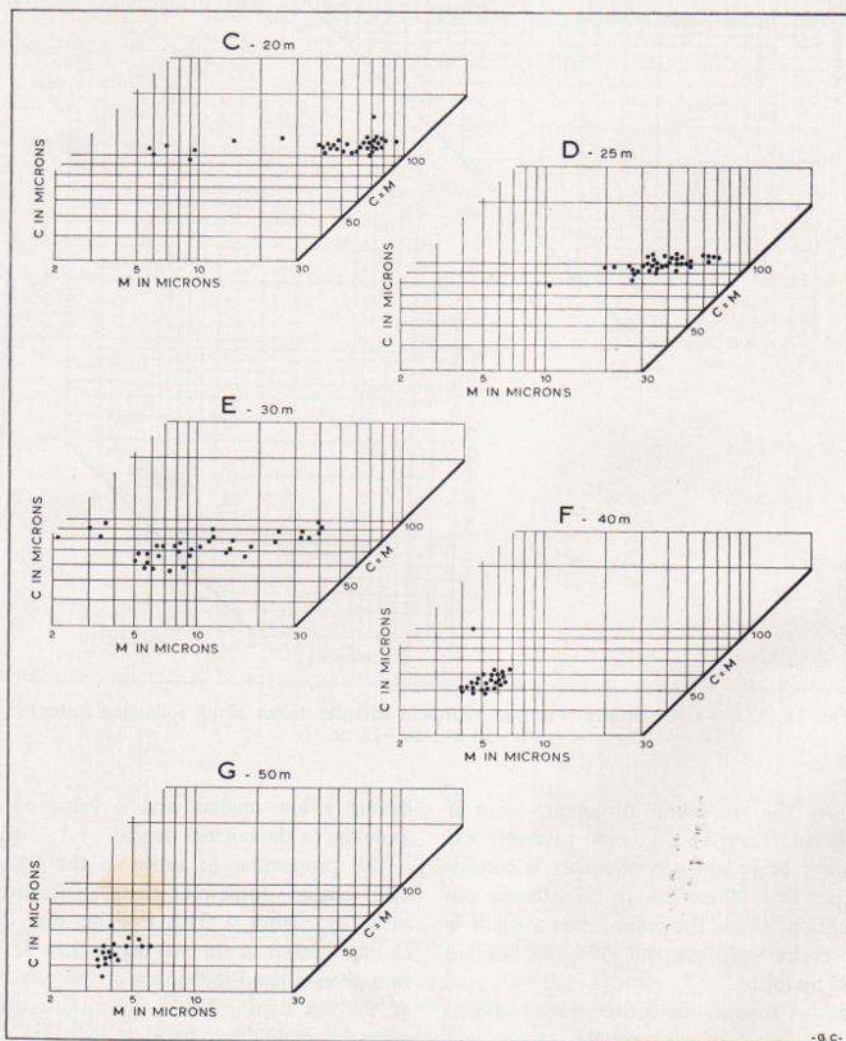

Fig. 11 C, D, E, F, G.—CM patterns. Patterns represent samples taken along following isobaths: C.—20 m.; D.—25 m.; E.—30 m.; F.—40 m.; G.—50 m.

III and IV, situated 1 and 3 kilometers, respectively, north of profile II, are supplied by longshore currents from the north. The sand is much finer than the sand of profile II. The sand percentage probably is high and deposits with a median larger than 30 microns extend to depths of more than 75 meters. In the area of profile V, it also can be assumed that the sand, transported by longshore currents around Point Conception, is reasonably free of lutite. The median decreases less with increasing depth than on the other profiles and is 200 microns at a depth of 20 meters. The present sea-level is recent. With time the sands of Point Conception should be able to construct an extensive sandy shelf.

The Adriatic coastal shelf is representative of conditions existing on many present shelves. Sediments supplied to the oceans by present rivers generally are fine. The sand percentage is low. It is approximately 5 per cent for the Niger (NEDECO, 1959, 1961) and 5 for the Mississippi. The abundant clay transported to the sea by rivers flocculates as it comes into contact with the sea water and largely settles near the coast where it builds a coastal shelf. On this shelf, fine sand forms uniform suspensions, and is kept in a narrow coastal belt by the high proportion of lutite in the sediments. The sand percentage in the available sediments can be increased by transport in longshore currents. This could lead to the construction of extensive shelves as suggested by profiles III and IV (Fig. 2).

The preceding discussion is limited to sediments transported by waves as uniform suspensions. This is far from being the only mode of wave transport. In numerous ancient shallow-water basins, sand predominantly transported as a graded suspension extensively covered the sea floor. Passega (1964) indicated that gravity probably was a controlling transport factor for many sand and sandstone deposits. As an example, in the Tertiary basins of the Po Valley, during certain periods of orogeny, rivers eroded considerable volumes of sand from the uplifted areas and transported dense graded suspensions to the sea. These suspensions consisted mostly of sand. They flowed on the sea bottom, seeking the depressions which were filled with sand deposits, commonly several hundred meters thick. In most of these basins, faunas indicate that the water was deep and that the deposits were turbidites (Byramjee
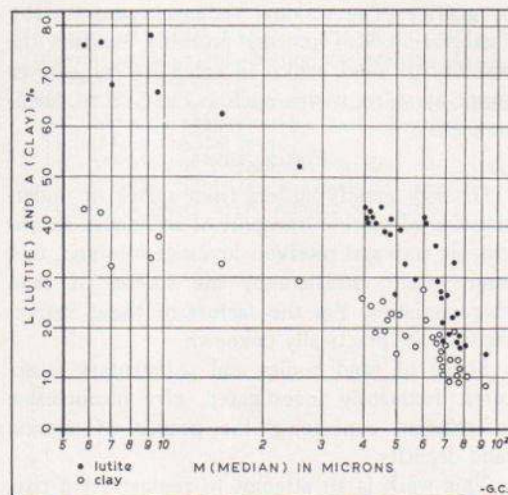

Fig. 12.—*LM* and *AM* diagrams for 20-meter isobath, showing variations of lutite (percentage by weight of fraction finer than 31 microns in bottom samples) and clay (percentage by weight of fraction finer than 4 microns) with median.

et al., 1965). In some, however, where the water was shallow, the distribution of graded suspension sands by waves was similar to the distribution of turbidites.

In ancient basins uniform suspensions commonly are associated with graded suspensions, probably as a result of wave action on the upper finer part of the graded suspension. Differential bottom turbulence seems again to control deposition as the graded suspension generally is deposited in more turbulent areas than the uniform suspension.

Rolled grains are common on ancient shelves in association with uniform suspensions. If the grains are rolled and deposited individually they are represented by scattered points on *CM* patterns similar to the pattern of Figure 11-B. Rolled grains may be concentrated in coarse-grained offshore bars. Because of their rugosity, these bars generally are free of fine sand. Differential bottom turbulence causes the deposition of uniform suspensions around the bar.

Finally, it may be noted that in some ancient Italian basins uniform suspension deposits and rolled grains were deposited on shelves while graded suspensions settled on slopes or in depressions. Selective transport probably removed the sediments which were more subject to the action

of gravity. The residual sediments are thereby "stabilized." This process probably explains the stability of sand banks on some Recent shelves swept by storm waves, such as the Gulf of Mexico shelf.

CONCLUSIONS

Geology greatly suffers from a lack of understanding of marine transport of sediments. Stratigraphic trap and reservoir investigations and, to a large extent, stratigraphy are studies of sand characteristics. Yet the factors of these characteristics are practically unknown.

Shape of sand bodies and sedimentary structures, frequently investigated, give inconclusive information concerning the genesis of marine sand deposits.

This work is an attempt to reconstruct a particular type of marine sedimentation; *i.e.*, distribution by waves on a coastal shelf having a uniform suspension consisting of fine sand and lutite.

Textural parameters of the deposits were found to be an orderly function of sea depth. The maximum grain size of the uniform suspension sediments regularly decreases with depth. The relation between median and depth is not as close, because of irregularities in the distribution of lutite.

Competency of waves does not directly control sediment distribution. The main factors of this distribution are differential bottom turbulence and grain size of the available sediments, which may be expressed as "sand percentage" in these sediments. The lutite contained in the suspension limits the seaward distribution of the sand by forcing it out of the uniform suspension. As a consequence, in the same area, at the same depth, and under the same wave regime, deposits may be sand or mud depending on the sand percentage in the available sediments.

The maximum grain size of uniform suspension deposits may, therefore, in a limited area, indicate the variations of the sea depth, but does not give the absolute value of this depth.

The sand percentage is extremely low in the sediments supplied to the sea by most modern rivers. In the sea, lutite flocculates and builds coastal shelves on which fine sand is distributed in a narrow coastal belt. Longshore currents transporting sand rather than lutite may increase the sand percentage in the available sediments. This sand probably would have built extensive shelves if time had not been short since the sea attained its present level.

Transport of uniform suspensions on the Adriatic coastal shelf is not affected by the action of gravity.

In ancient seas, at times, conditions were different. Rivers, flowing in mobile areas, eroded considerable volumes of sand which formed dense graded suspensions in the sea. These flowed by gravity either as turbidity currents or as wave suspensions and formed extensive blanket sands.

Grain size is therefore a major factor of marine sedimentation as it may determine the transport mechanism and control the sediment distribution. Textural studies disclose close relations among basic factors such as orogeny, grain size of river loads, grain size of marine suspensions, submarine topography, and distribution of sand. Investigation of these relations is essential to the understanding of the dynamics of sedimentation. This is a relatively new field which offers to the petroleum geologist the possibility of making substantial progress in mapping and projecting the characteristics of terrigenous deposits.

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