THE CONTRIBUTION OF SEDIMENTOLOGY TO HYDROGRAPHY IN THE STUDY OF COAST AND ESTUARY CHANGES

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INTRODUCTION

The early hydrographers were already practising sedimentology when they examined materials brought up from the sea bottom by greased hand leads and noted on their charts : — sand — silt — mud, or even at times rock, though this was a supposition. It is extremely interesting to find these remarks on the old maps when assessing later research.

Geologists, for their part, were taking an interest in marine sedimentation and we recall the names of Dangeard and his work in the English Channel, Berthois in the Loire estuary, Rivière on the Vendéan coast, Glangeaud in the Gironde River, Bourcart in the Mediterranean.

However, it is only in recent years that young sedimentologists, notably students of Professor Rivière, have agreed to abandon individual research and to be included in technical groups studying the sea shores and the mouths of the estuaries. In such an organization, the information obtained on site by the hydrographical, oceanographical and sedimentological teams is immediately analysed in the field and then the investigation programme of the whole group is modified in order to arrive at its desired end in the shortest possible time.

This end consists of defining the regime of a coast or an estuary within the geographical boundaries previously decided, but principally of *analysing the movements of the ground materials, including :*

1. *Determination of their source;*
2. *The courses followed and conditions for movement;*
3. *Estimation of the rate of materials in suspension.*

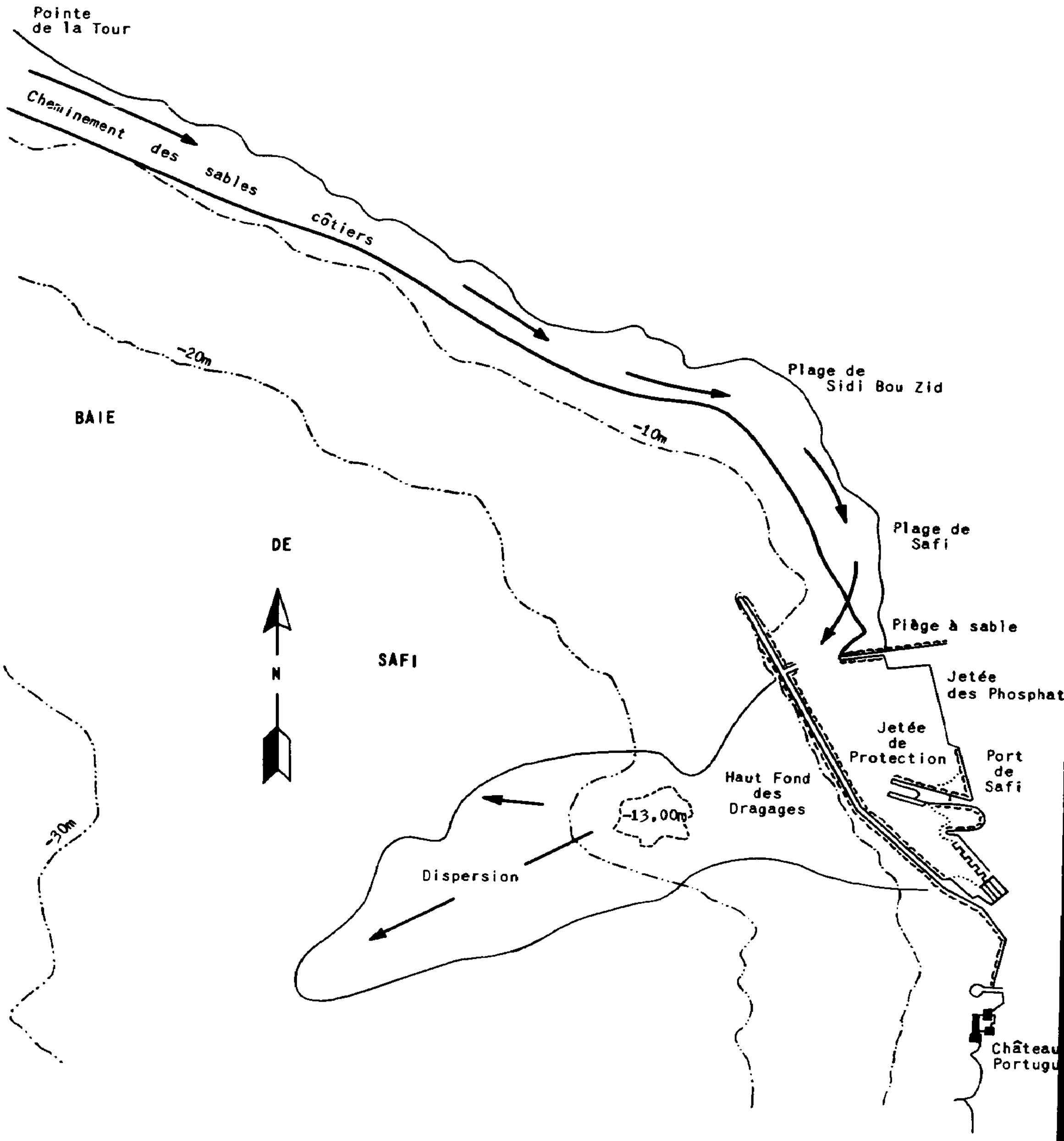
Although there is no obvious division when considering grain sizes the sedimentologists have deemed it necessary to divide the materials into two groups : one coarse, i.e. *sand,* the other fine, i.e. mud (*pélites*), the dividing line being a diameter of *80 microns.*

PLANCHE I

BAIE DE SAFI

SCHEMA DU MECANISME DE L'ENSABLEMENT

ECHELLE : 1/20 000



Problems are relatively simple when the materials in movement are only sands shifted on the sea bottom, since their movement is relatively slow and easily followed without the help of radio-active tracers. On the other hand, the problems become very complex when the pélites are carried in suspension and sands shifted at the same time, as in estuaries.

It is not up to us — and besides this would require a full report — to give a detailed account of all sedimentology techniques. We merely propose to show with the help of two typical known examples what can be expected from the fruitful collaboration between the hydrographers and geologists of the Ports Study Group.

The examples are :

The *open coast* at Safi [1] where it was only a problem of sands

and

The Gabon *estuary* where the whole range of materials was involved.

EXAMPLE OF AN UNI-DIRECTIONAL MOVEMENT OF LITTORAL SANDS ON THE OPEN COAST

The movements of littoral sands on an open coastal area are due exclusively to three forces of nature [2] : the sea, the wind and the currents. When the action of at least one of these forces is directed sometimes in one direction and sometimes to the other in relation to the normal to the coast, the movement also *alternates* and then becomes much more difficult to define and to measure.

With a view to illustrating the coordination between the hydrographic and sedimentary work, and to avoid confusing readers, we have chosen an example both clear and rich in information, i.e. the Bay of Safi, where the movement is exclusively sand and purely *uni-directional.*

Historical summary of the construction and silting-up of the Port of Safi

The port of Safi, at the far end of a large bay of the same name (see fig. I) has for a long time been reduced to a wharf constructed in 1908

(1) The study carried out at Safi in 1948 and 1949 was under the control of the Laboratoire Central d'Hydraulique de France. Readers of the International Hydrographic Review who wish to obtain all scientific and technical details of the study of Safi should consult :
— Reports of the Académie des Sciences Meetings, Vol. 230, pages 2037 to 2039, meeting of 5 June 1950. — Oceanography — Scientific findings of a hydro-oceanographic study group at Safi; littoral phenomena. A note by M. Jean Laurent and M. André Rivière introduced by M. Donatien Cot.
— 9th General Assembly of the Union de Géodésie et Géophysique Internationale at Brussels, 1951. — Physical oceanography section, an article submitted by M. Jean Laurent : Results of the Safi Harbour Study Group.

(2) In 1950 the beach at Tanger was periodically reshaped by bulldozers and, for so long as we were unaware of this fact, the remarkably flat profile of this beach was a puzzle to us.

200 metres to the north of the Château Portugais and carried out as far as the 5-metre depth contour.

This open construction did not disrupt the general process of shifting along the sandy coast. Whilst the wharf remained it was impossible to see any appreciable change in the sands along the Sidi Bou Zid beach and the large beach of Safi terminating at the foot of the Château Portugais.

Damaged by waves, the wharf was no longer adequate for the increasing traffic and a harbour was built between 1921 and 1935, including in its main features :

— a large breakwater 1 500 metres long, beginning on the coast 300 metres north of the Château Portugais, reaching the 13-metre depth contour, and then following it in a N-NW direction;

— a transverse jetty 800 m long to the north of the beginning of the breakwater.

This wharf, acting as a dyke, soon blocked a large movement of sand which resulted in obstructing the entrance channel. It was therefore necessary to dredge and maintain constantly a sand-trap to the north, near the transverse jetty, in order to keep the access to the harbour clear.

When the coastal survey party arrived at the site in 1948 to analyse the general mechanism of the silting-up, there were many varied opinions. Some observers thought that the sand came from Sidi Bou Zid to the north; others from the Château Portugais to the south, and others again thought that it was brought in by the sea. It was, therefore, without any preconceived idea that we started work.

Hydrographic results

In the course of a series of measurements which lasted approximately one year, from August 1948 to July 1949, the hydrographic section of the coastal survey party drew the following major conclusions :

1) *Stability of the middle depths* (below the 13-metre depth contour)

The master of the dredger operating to the north of the phosphates jetty had the fortunate idea of always tipping the dredged materials at the same point. As a result of a large-scale hydrographic survey we found on the sea bottom a large deposit rising to the 13-metre depth contour. This deposit was 1 800 000 m^3, corresponding approximately to the total volume of the dredged materials from which it was made, i.e 180 000 cubic metres per year for 12 consecutive years. Thus, the swell, though very strong at this point in the Bay of Safi, was shown incapable of moving sediments below the 13-metre depth curve. From this exercise we thus learned the range in depth of swell action.

2) *Rapid changes in the profile of the shore*

On the other hand, along the coast on the upstream side of the phosphates jetty the shape of the sandy beaches and the consequent shallows showed the marked effect of the breakers on the littoral sands and their progressive shifting action towards the sand-trap. The Sidi Bou Zid and Safi beaches serve as " relay stations ", sometimes being built up by medium swells with sand removed from shallow waters, sometimes emptying them of sand because of strong swells from the west, redepositing it in these same shallow waters.

3) *Measurement of swell currents*

During storms it was possible to measure the swell currents caused by the sloping profile of the waves, which rapidly increased in strength with the degree of agitation. Turbulence is the main factor governing the littoral transportation of sand, since it draws up the deposits from the sea bottom and holds them in suspension. Even a very weak current which could never have moved them in calm weather becomes capable of transporting these deposits.

Most swells came from the NW and W. Therefore along the north coast the obliqueness of the wave crests could only give rise to movement towards Safi harbour. A turbulent current along the length of the phosphates jetty moved towards the entrance channel and, because of the coastal sands that it carried, threatened to form a "tombolo". These facts we learned during bad weather. Above the deposit of dredged materials the current flowed to the SW, which, as we will show later, is in agreement with the dispersal course taken by the fine materials in suspension.

Sedimentological results

The geologists who took part in the study at Safi submitted the following detailed information :

1) *Precise identification of the materials invading the harbour entrance*

With the help of the very simple laboratory equipment available on the site (magnifying lens, drier, balance, etc.) the sand from the sand-trap was identified by its colour, its morphology, the proportion of calcium, and most important of all, by its grain size.

At the present time very elaborate methods, using a series of sieves, are being employed in order to plot on a graph both fully and accurately the distribution of grain sizes in a specific sample. However we were at that time satisfied with dividing each sample into 3 groups :

— the large grains, which remained in the size 80 mesh sieve, i.e. having a diameter of greater than 0.225 mm;
— the middle-sized grains, sands retained by sieves between the 80 and 120 mesh sizes, i.e. between 0.146 and 0.225 mm diameter;
— the fine grains, consisting of material passing through the 120 mesh sieve, i.e. less than 0.146 mm diameter.

The material deposited in the sand-trap consisted mainly of largesized sand grains. The next step was to compare these with samples taken both along the coast and out to sea.

2) *Extent of littoral movement*

Having carried out a series of sampling tests along radials roughly perpendicular to the coast line, a graph was drawn showing in ordinates the histograms of the three different groups along each radial, (the distances being represented on a suitable scale by abscissae).

It was thus possible to see that the coastal sea bottom, as far out as a depth of between 5 and 10 metres (according to the degree of exposure to swell action), was covered with the same large- and medium-grained sand as that found in the sand-trap. At a greater depth the fine-grained sand became predominant.

It was therefore possible, by using these radials, to plot the envelope of littoral movement. It began in the north and followed the base of the jurasic-chalk, a formation incapable of supplying it with material.

3) *Proof of the dispersal phenomenon*

As was expected, the measuring of the grain sizes confirmed the relationship between the coarse sands from the deposit of dredged materials and those from the sand-trap. However, the radials crossing this deposit showed the existence of an additional phenomenon. This was the scattering of the finest-grained sands around the deposit, and particularly in the SW direction, following exactly the line of the current measured during bad weather in Safi bay.

Similarly, along the sandy coast, the alternate mixing of materials in cross-section is accompanied by a progressive elimination of the fine-grained materials as they are dispersed out to sea. The particularly coarse sand found on the beaches and in the coastal waters is due to the sifting action of the large breakers along the Atlantic coast of Morocco.

4) *Determination of the sediment-producing zone*

The analysis of the fossilized dunes in the Cantin-Oualidia region, from a point situated 20 kilometres north of Safi showed that the sand, on being broken up by the action of the sea, is identical (from the morphological, lithological and granularmetric point of view) to that which arrives in Safi Bay after rounding the Pointe de la Tour.

General Synthesis

By combining the hydrographical and sedimentological studies, from which we extracted a general outline, we were able to analyse the general mechanism of the silting-up at Safi.

The coarse sands produced to the north of Cape Cantin by the destruction of the fossilized dunes are carried towards Safi Bay by the unidirectional swell currents. These currents deposit material in the surf zones along the beaches located between rocky points.

After the construction of the harbour, the littoral movement was blocked by the phosphates jetty and the sand was deposited along this artificial sand-trap at the average annual rate of 180 000 m^3.

The medium depths remain stable, at least up to a depth of 13 metres, in a region particularly influenced by swell, but are gradually filled in by the scattering of fine-grained sands coming from the coast and from the dumping area of the dredger.

This simple and irrefutable analysis of the littoral phenomena at Safi was only obtained after much trial and error. It is precisely thanks to the overlapping of geological and hydrographical research, the one helping the other, that the study was concluded within the specified time limit.

EXAMPLE OF THE MOVEMENT OF SANDS AND PELITES IN AN ESTUARY

Aim of the study of the Gabon estuary

It is well-known that the Gabon estuary (see fig. II) is listed for development, as the harbour facilities at Libreville do not offer opportunity for much improvement because of the distance to the 10-m depth contour, the presence of rocky shoals and the difficulty of developing buildings and working areas.

On the other hand, the exportation of iron-ore from Mekambo will necessitate the creation of a specialized port which was first intended to be at Pongara Point, on the other side of the estuary.

Finally it was considered advantageous to build at the same time a commercial port and an ore-exporting port, one beside the other, at Owendo Point, situated at the far end of the estuary on the edge of a channel 14 metres deep (see fig. II).

After a brief primary hydrographical investigation in 1960, an additional survey was made from July 1962 to May 1963 with a view to confirming the suitability of the Owendo site for a port. In this large estuary, 15 km wide at Pongara and 15 km long between Pongara and Owendo, the Service Hydrographique de la Marine had just carried out a new general survey at the scale of 1/25 000, which enabled the survey party to devote itself to its own work, i.e. :

- a large-scale hydrographic survey (1/2 000) of the area surrounding Owendo Point, including a study of the sub-bottom;
- an investigation of the sea bottom along the line of the entrance channel which is to be dredged to enable vessels of 12-m draught to berth at Owendo at any time, and a study as to the suitability of the sand deposits as fill for the port area;

— marine hydraulic, hydrological and sedimentological measurements to determine the regime of the estuary.

From this it can be realized that even work specially needed for establishing a port substructure would lead to a better understanding of the movement of materials, and in this field we will now show the effect of the joint efforts of the hydrographer and sedimentologist on the site.

Hydrographic results

From the work they did themselves and from the notes made during former hydrographic surveys the hydrographic section of the survey party reported their principal results as follows :

1) *The limits of the rocky bank of Owendo*

A vast rocky spur leading from Owendo Point was mapped out by divers equipped with hydraulic probes. The rocks were bare in the region of the reef, as was found by a previous survey directed by Mr. Le Fur, Ingénieur en chef, of the French Hydrographic Office. Elsewhere, the rocks were hidden under a deposit of materials of varying thickness.

During ebb tides the current is confined to a specific channel by this rocky spur and Owendo Point, and this explains the maintenance of an isolated deep to a depth of 14 m, as confirmed by successive surveys since 1912.

2) *General modification of the sea bottom*

A new survey of the sands at Pongara Point showed that it has retreated by 500 m during the period 1956-63. Pilots from Libreville had moreover already noticed this fact.

In the bay of Igoumé, i.e. between Owendo Point and Coniquet Island, a general rising of the sea-bottom was noted by comparing several consecutive surveys, and a channel bordering the Bank of Cigognes has been partly filled in.

On the other hand, from Owendo to Pongara the difference between the soundings in 1889 and 1956 does not establish with certainty a general rising of the sea-bottom, since the methods of sounding used were not the same. The hand lead sinks into the mud, whilst the U.S. survey measured the depth to the upper surface of the mud.

3) *Movement and Currents*

The propagation of swell through the estuary has been studied. Outside the estuary the swell from the SW often has a range of 2 m and a period of 10-12 seconds. Subjected to a turn of more than 90° around Pongara Point, deflected by the Banc de la Mouche and weakened by passing over successive banks it reaches Owendo with only a negligible range (0.20-0.30 m) and a shorter period of 4-5 seconds. Most of the movement of water in the estuary is caused by winds from the SE in the morning blowing down the estuary, and from the West blowing towards Owendo in the afternoon. To these regular winds we must add the brief, localized but violent tornadoes.

The new tracks taken by the currents around Owendo Point were measured, showing very clearly the predominance of a strong ebb current of about 2 m/sec over a rising flow of about 1 m/sec during Spring Tides.

At Owendo it happens that at the lowest Neap Tides the flow finally disappears for nearly three hours following Low Water.

The current was also measured at several points distributed along the estuary. Samples of water were taken every hour at three depths (1 m below the surface, in mid-depths, and 1 m above the bottom) during a complete 12-hour tide to measure the salinity and turbidity.

Sedimentological Results

Numerous water samples and 130 samples of the bottom surface layers distributed over the complete estuary, upstream, downstream and at its mouth, were given to the sedimentologist who was to carry out a detailed study.

To avoid too many consignments to France, that part of the analysis which did not require costly and accurate instruments was carried out at Libreville by the C.E.B.T.P. laboratory. An identical procedure had been carried out several months before at Douala for the study of the Wouri estuary. We show in fig. III several photographs of the laboratory designed by the Port Authorities which can be considered as a model of its kind — spacious, clean and air-conditioned.

In these site laboratories measurements are made of the " pH " value, salinity, turbidity, water content, proportion of pélites i.e. materials passing through a sieve with a mesh of 80 microns.

The geologist who had already flown over the Gabon estuary, during July and August 1962 drove round the edge by car, and went up the main branch channels in a launch. He then carried out additional analyses of the sediments in the Sedimentology laboratory at Orsay University, using the most up-to-date mineralogical, morphoscopic and granularmetric methods. He then employed the hydrological and sedimentological data, comparing it with geological information previously obtained. The major results thus obtained were the following :

1) *Elimination of the risk of silting-up at Owendo*

Each sediment core obtained contained a certain proportion of sand and pélites. These two groups are distinguished, as has already been stated, by the diameter of 80 microns.

From fig. II it can be seen that sand is clearly dominant (in excess of 90 %) along the coast from N'Gombé to Pongara and penetrates into the estuary where it disperses to both sides of the deep channel along the left bank.

Isolated deposits of limited extent are found at the edge of Perroquet and on the right bank upstream of Owendo.

Morphologically the sands on the right bank are different from those at Pongara and therefore a heavy and continuous movement of sand similar to that at Safi is not to be feared near Owendo. Furthermore the swell is completely subdued and stronger ebb currents tend to drive the materials in a downstream direction.

2) *Importance of wooden debris in the mud*

Numerous mineralogical and quantity analyses to determine the iron and calcium content of the mud did not give any definite results. These analyses confirm, however, that the present deposits in the Gabon river and the earlier deposits in the mangrove swamps originated from the renewed erosion of an old deposit through the alternating movement of the estuary's tidal waters. The results obtained can only follow from regular alternating conditions in the estuary. The smaller the Como basin is, all the more lost in the existing sands of the estuary are the materials contributed by the river.

Stocks of wood are present in Igoumé Bay. Large quantities of wooden debris in the mud, making up 2/3 rds of its volume, form a spongy matrix in which mineral elements are scattered. This has been noted around Owendo, and is a common phenomenon. This matrix has an exceptional water-retaining capacity (maximum 722 %) and is very resistant to consolidation.

3) *Lack of salinity variation in the estuary*

From 500 samples examined in the rainy season, the salinity only varied between the extreme limits of 18.0 g to 29.5 g per litre. These values, compared with the average value of the open sea (35 g per litre) show that the sea waters are to some extent diluted by the waters from the rivers (the Ogoue, and even the Congo) because the small area of the Como basin is not sufficiently large to produce this effect.

Moreover, the values of salinity taken at various points up and down the estuary remain noticeably constant at all times during the same tide. The contribution made by the waters of the Como, and hence the rate of materials in suspension, is therefore negligible.

4) *Estimation of the rate of materials in suspension*

The examination of numerous turbidity measurements during a tide cycle did not show that mud was carried in preference to other materials. The increase in the rate of materials in suspension is apparently caused as much by chance local conditions as by the tide cycle. This is all the more remarkable because the current speed at ebb tide is twice that during flood tides.

In the estuary the turbidity is consistently greater in the vicinity of Owendo than either upstream or downstream. This can be explained by the turbulence in this transit zone.

As is normal in estuaries, the turbidity increases rapidly with the speed of the current which stirs up the loose materials on the bottom. The turbidity in the Gabon varies from 1 to 10 according to whether it is a Neap Tide or a Spring Tide. There is little seasonal variation.

Near the surface the mud content is small and it is unusual to find even a few decigrams per litre. At mid-depths there is still little turbidity. From one metre above the bottom there is a much more rapid increase in a vertical downwards direction, and without physical discontinuity we pass from heavily-loaded water (containing 10 to 20 grams of solids per litre) to extremely fluid mud, and then to more dense mud containing less water. In order to check this phenomenon we carried out direct sampling with the help of frogmen. A stake was driven into the loose materials on the bottom and samples were taken of first the water and then the mud at every 0.50 m.

With the help of all the data obtained, it was possible to estimate approximately that 10 to 15 million cubic metres of liquid mud at an average specific gravity of 1.15 was put in motion at each tide in the Gabon estuary.

This large rate of materials in suspension does not necessarily collect at any one area, since it circulates in a regular but variable pattern, as already described, the deposits compensating for the erosion.

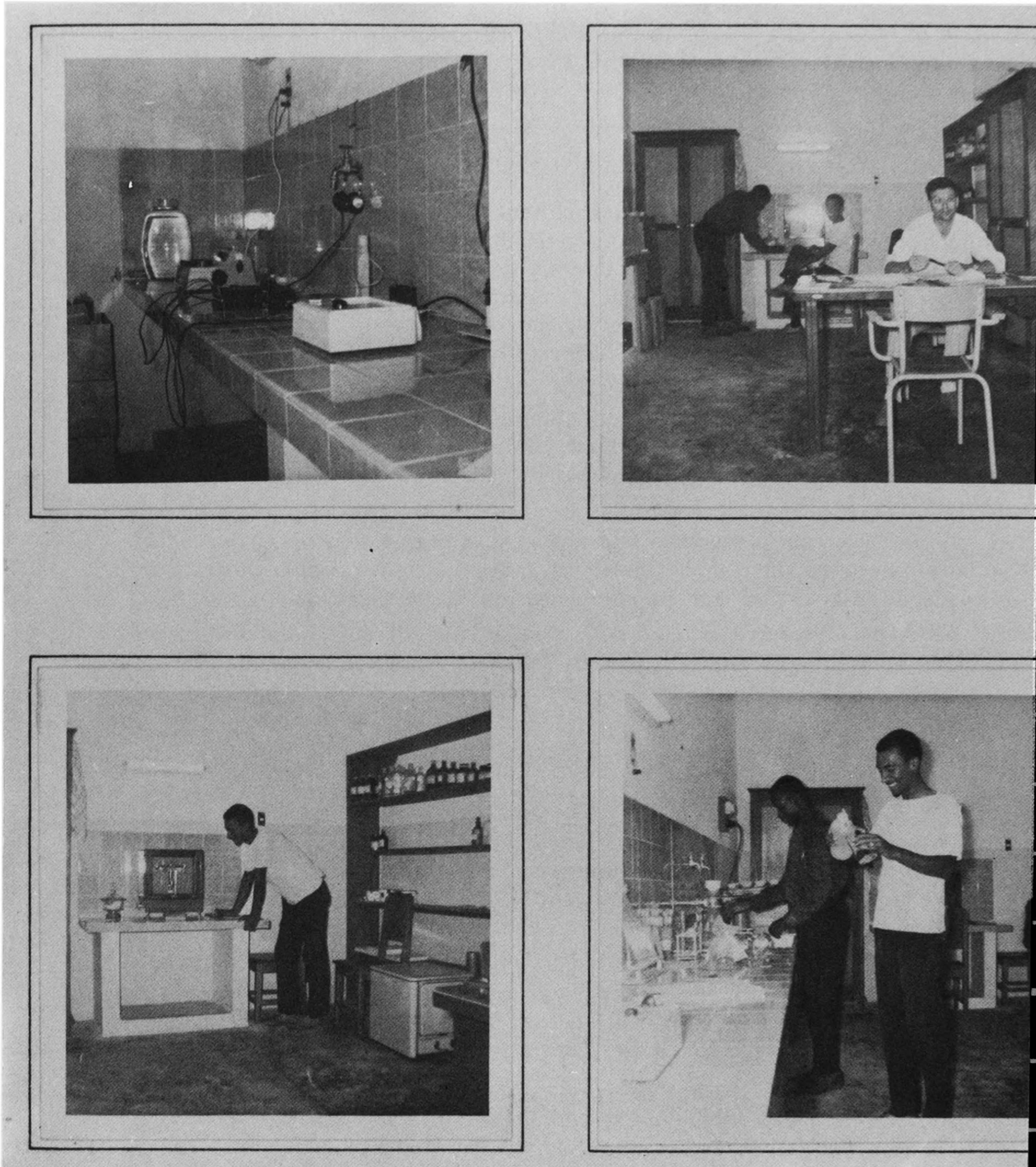
Any deeply dredged channel, though at present none is under consideration, might well disturb the present state of balance between Owendo and the beginnings of a deep channel on the left bank of the estuary.

General Synthesis

The hydrographical and sedimentological studies make it possible to remove any *fears of silting-up* at Owendo Point. The Pongara site initially proposed, however, is subject to a great deal of movement which may considerably hamper port installations.

At Owendo itself, the rocky underwater bank, together with the scouring movement of the tide at Igoumé Bay, helps to maintain a deep channel of 14 m. Here the largest of the present day ore-carriers could berth.

Within the wide channel, 10 m in depth, which links Owendo across the estuary to the deep channels along the left bank, an entrance channel should be dredged. For vessels not exceeding 12 m in draught this channel will only need to be deepened by approximately 1.5 m. There will be no need for much dredging to keep the channel clear. Moreover the movement of the propellers will easily stir up the deposits because consolidation is particularly slow due to the enormous water-retaining capacity of the abundant wooden debris.



Laboratory of sedimentology.

CONCLUSION

No attempt should be made to apply the two preceding examples directly to any future study of a coastal area.

However, with the larger draught of the ships of to-day and the obligations that naturally follow (i.e. the deepening of channels and the increase in maintenance dredging), we believe that these examples will have proved of present-day interest.

They have lead not only to the definition of the sea bottom at a given time but have also helped both to provide for its natural evolution and the effect of this evolution on port and defence works and on deep entrance channels.

It is evident that valuable knowledge is given to the hydrographer by the geologist, enabling him to identify both stationary material and material in transit, to estimate the average rate of material in suspension and to track the courses followed and pinpoint their origin.

These specialists, by uniting their efforts on the site, and by pooling the necessary equipment, are able to solve problems of the movement of deposits both rapidly and at little cost.

Doubtless the phenomena of sand-shifting movements are now more within our grasp than the settling of marine material in suspension, but the progress made in sedimentology is rapid, and it now has at its command new scientific methods and a great deal of experience.