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Study of Fine Material in Suspension in the Estuary of the Loire and its Dynamic Grading[a]

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The tidal and seasonal movements of the turbidity maximum and the fluid mud layer of the Loire estuary were investigated and related to the concentrations of different clay minerals. The concentrations of Illite and Montmorillonite are shown to be inversely related, while Montmorillonite reaches a maximum concentration, approximately 40% of clay minerals present, in the zone between the turbidity maximum and the fluid mud. Seasonal variations show that the concentration of Montmorillonite moves with the turbidity maximum.

Introduction

The dynamics of suspended sediments in the estuary of the Loire are affected by the occurrence of two quite distinct mediums: the turbidity maximum and the fluid mud which are two complementary aspects of the turbid accumulations in the estuary. As such, they govern the phenomena of silting whose cycle is further complicated by the influence of bottom sediments, upstream and downstream deposits, mudbanks, etc. However, examination of weighable percentages of suspended argillaceous minerals and their X-ray analysis allow the behaviour of materials in suspension to be determined within the framework of these two dynamic phenomena.

Dynamic phenomena

Turbidity maximum

This phenomenon, discovered in the Gironde by Glangeaud (1938, 1941) has been studied in detail by Berthois (1954, 1955, 1956, 1964) in the Loire estuary. It is an area of high turbidity produced by a concentration of fine sediments carried in suspension. 'It extends over the whole of a zone where, at a point in the tidal cycle, the turbidity attains a value distinctly greater than that of the suspensions coming from upstream which is not subject to the dynamic tide' (Berthois 1955, p. 106).

[a]Work carried out with the co-operation of Port Autonome de Nantes-St-Nazaire and C.N.E.X.O.

The Loire estuary can, therefore, be regarded as a turbidity maximum area since the turbidities are greater than 50 mg/l and less than 10–20 g/l. At each tide, the turbidity maximum passes into the estuary; it is forced upstream at high tide and is expelled downstream at ebb tide. This oscillation is a function of the flow of the Loire and of the tide coefficient. At an average discharge (800 m^3/s) it oscillates between Donges and Le Pellerin. When the river is in spate (1 000–4 000 m^3/s) it is located in the downstream section of the estuary and may even be expelled into the sea towards la Pointe St. Gildas. At low discharge, however, it moves back upstream and during high tide coefficients (spring tides) can move as far up as Nantes. In such conditions, heavy silting-up of the port of Nantes can occur as, for instance, happened in August 1949 when an exceptionally low flow rate of 48 m^3/s and spring tides brought about the deposition of 500 000 tons of material.

In the same way in 1972, a similar movement and corresponding silting-up occurred following a prolonged low-water level.

Fluid mud

This is a highly concentrated, dense mass, located close to the bottom in the middle of the estuary. Turbidity here is greater than 20 g/l but can attain extremely high values of from 400–500 g/l. The formation generally takes on the form of a lens with a length of from 1–10 km and a height of from 0·50–2·50 m.

Because of its density, which is much greater than that of the water, the fluid mud is easily detectable by ultrasonic depth sounding (Figure 1). Bottle samples show that the fluid mud always has a turbidity in excess of 20 g/l and that it is relatively independent of the overlying water because of the non-miscibility of two liquids of largely differing densities (in particular that of the turbidity maximum). Transition between the fluid mud bed and the turbidity maximum takes place over only a few decimetres.

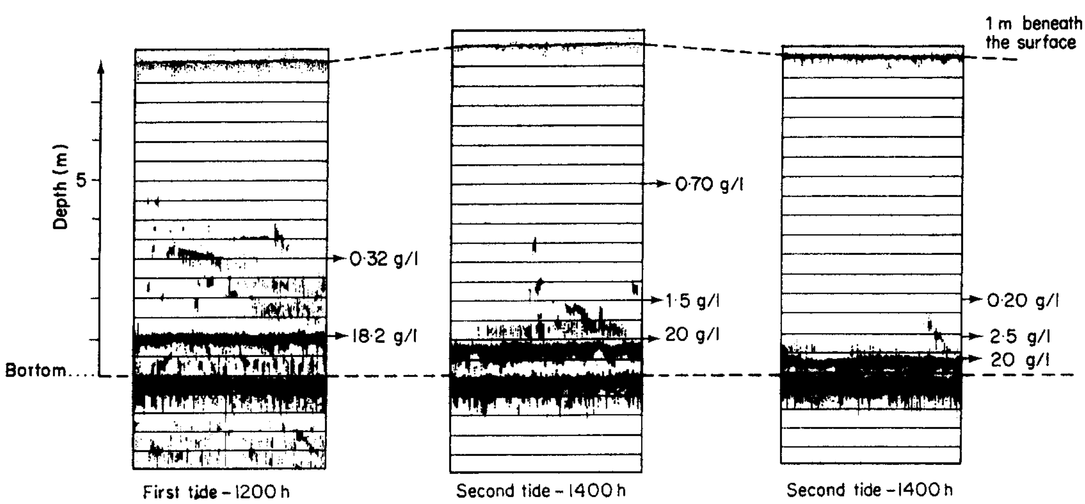

Figure 1. Ultrasonic detection of the fluid mud and comparison with calculated turbidities.

The movement of the fluid mud is slight; only a few hundred metres per tide (Courtois, G. & Anguenot, F., 1968). It does, however, undergo large seasonal displacements along the length of the channel due to the flow of the Loire and this has been well observed in successive ultrasonic depth soundings.

A statistical study is at present being undertaken on the basis of the soundings, made since 1964, to study the influence of the flow of the Loire and the tide coefficient on the position, length, height, etc. of the fluid mud.

In the case of average flows, the fluid mud is located in the area from Paimboeuf to La Marechale. On the other hand, when the river is in spate, it is found to be expelled downstream, between Donges and St. Nazaire, whereas in the low water period it moves upstream as far as Pellerin. It is during this period that it has its maximum extension.

The risk of a port silting up due to such a formation, when there is a relative calm, is obviously much greater than that due solely to the maximum turbidity. It is for this reason that an investigation into the displacement of the fluid mud assumes such importance in port maintenance.

Relationship between the turbidity maximum and the fluid mud

In a recent work (Gallenne, B., 1971), we analysed these two dynamic phenomena, at a fixed point, over the following four tide coefficients: 30, 50, 70 and 90.

We showed that the fluid mud is enriched in slack water through the settling of the material contained in the upper water layer and, in particular, from the maximum turbidity. This enrichment is more important during neap tides. On the other hand, particularly at high tides and to a less extent at ebb tides, when the current is strong, all or part of the fluid mud is taken back into suspension depending on whether there is a large or small tide coefficient.

This return of the fluid mud into suspension by the current brings about the resupply of the maximum turbidity. In such cases, the fluid mud may distinctly diminish and even disappear. In the next slack water period settling restores the fluid mud.

However, the physical character of these two turbid formations remain quite distinct. Salinity measurements taken at the level of the fluid mud vary slightly from those taken in the overlying water and in the turbidity maximum (variations in the region of 5 parts ‰). The fluid mud behaves like a fluid medium independent of the water which surmounts it and there is a very slow salt diffusion between the water and these beds. This phenomenon has also been noted in the Gironde (Allen, G. P., 1971).

The fundamental difference is the permanent existence of the turbidity maximum in the estuary whereas the fluid mud exists only in a temporary state. In fact, the existence of the maximum turbidity can always be detected either in transit within the estuary or completely expelled into the sea. The fluid mud, on the other hand, is often undetectable during very high tides, when the tide coefficient is greater than 70, or when water mixing prevents its further formation.

Analysis of argillaceous minerals in suspension

Samples were taken in 20–30 l-capacity polyethylene drums using a hand pump which, after decantation, enabled 1–5 g of sediment to be recovered. The making of laminae from these sediments and the identification of argillaceous minerals by X-ray were carried out using the methods recommended by Lucas *et al.* (1959).

A quantitative approach was made by considering the height of the peaks of the different lines with an approximation in the order of 5–10%. From the qualitative point of view no variations were noted in the argillaceous phase usually present in the estuary. The essential minerals were always: Illite, Montmorillonite, Kaolinite and Chlorite. Interstratified minerals were rare and were of the type Illite/Montmorillonite and Montmorillonite/Chlorite. The chance occurrence of Pyrophyllite and Halloysite, essentially detrital and local in origin, should be noted.

From the quantitative point of view an appreciable longitudinal alteration was noted. We have shown the variations in the different argillaceous minerals met in Figure 2.

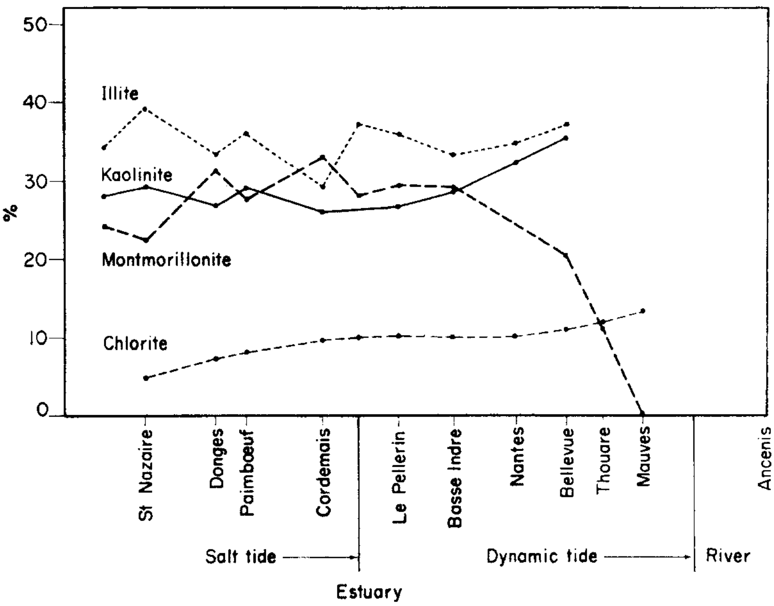

Figure 2. Longitudinal variation of suspended argillaceous minerals in the Loire Estuary.

Kaolinite

The percentage of Kaolinite is constant (30%) over the whole of the estuary but there is a slight increase in the upstream sector indicating a continental detrital origin.

Chlorite

In spite of its low percentage in the estuary (5–15%) it was possible to track its alteration; there is a progressive diminution in the downstream direction in addition to a continuing degradation of the Chlorite along the whole length of the estuary, similar to that noted in the Gironde (Lafond, 1972).

Illite

Overall, the Illite is stable in the estuary at around 30–40%. It does, however, vary in inverse proportion to the Montmorillonite.

Montmorillonite

Apart from its close relationship with Illite it is of interest to note a concentration of Montmorillonite in the suspended sediments in the depths of the estuary. In the middle of the estuary, the Montmorillonite has a value of from 30–35% whereas towards the open sea, this drops to around 20% and may even, at times, in the upstream zone, vary from 0–20% at the Nantes level.

The overall variation of suspended argillaceous minerals produces two important affects:

the inverse relationship between Illite/Montmorillonite;

the concentration of Montmorillonite, of dynamic origin, in suspension, in the interior of the estuary.

The corresponding measurements of turbidity show that this concentration in Montmorillonite in the middle of the estuary is closely bound to turbidity maxima as we shall see in the following section.

Relationship between montmorillonite and the turbid zones

General study

In order to show the relationship between the argillaceous material, rich in Montmorillonite, and the dynamic phenomena, we have plotted the variation in the percentage of Montmorillonite as a function of turbidity (Figure 3).

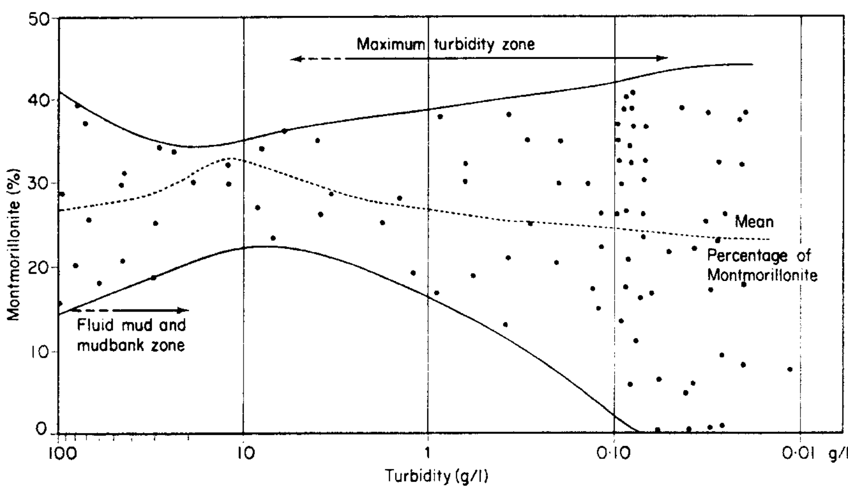

Figure 3. Relationship between turbidity and the percentage of Montmorillonite.

In the turbid zones, it can be seen that the percentage of Montmorillonite is always high (average 25–30%), however, it is in the transition zone between the fluid mud and the turbidity maximum of about 20 g/l, that the Montmorillonite has its most constant and highest percentage (30–35% on average). It is, therefore, in this intermediate zone that the Montmorillonite is concentrated.

In the region of the turbidity maximum the percentages of Montmorillonite vary widely (from 0–40%) at a rate and amount governed by the turbidity. The highest percentages are seen when there is a recovery to suspension from the zones rich in Montmorillonite (the top of the fluid mud and the lateral mudbanks). The lowest percentages, on the other hand, are to be found in the upstream zone of the estuary where the Montmorillonite is very low or even completely absent, or outside of the estuary.

This general study, therefore, shows two important features:

(i) a concentration of Montmorillonite in a zone where the percentages in the turbidity maximum and the fluid mud are similar

(ii) the possibility of utilising Montmorillonite as an indicator of displacements of the fluid mud and the turbidity maximum since it is concentrated between the two.

Relationship between Montmorillonite and the fluid mud

Vertical study at fixed points. Vertical readings of turbidity taken over several expeditions, have shown that the behaviour of the argillaceous minerals varies in relationship to the existence or absence of the fluid mud (Figure 4). Samples taken during the absence of the fluid mud (LA-L J) show a homogeneity in the percentages of the various clays with depth. On the other hand, samples taken when the fluid mud is present show a differentiation in the distribution of the argillaceous minerals:

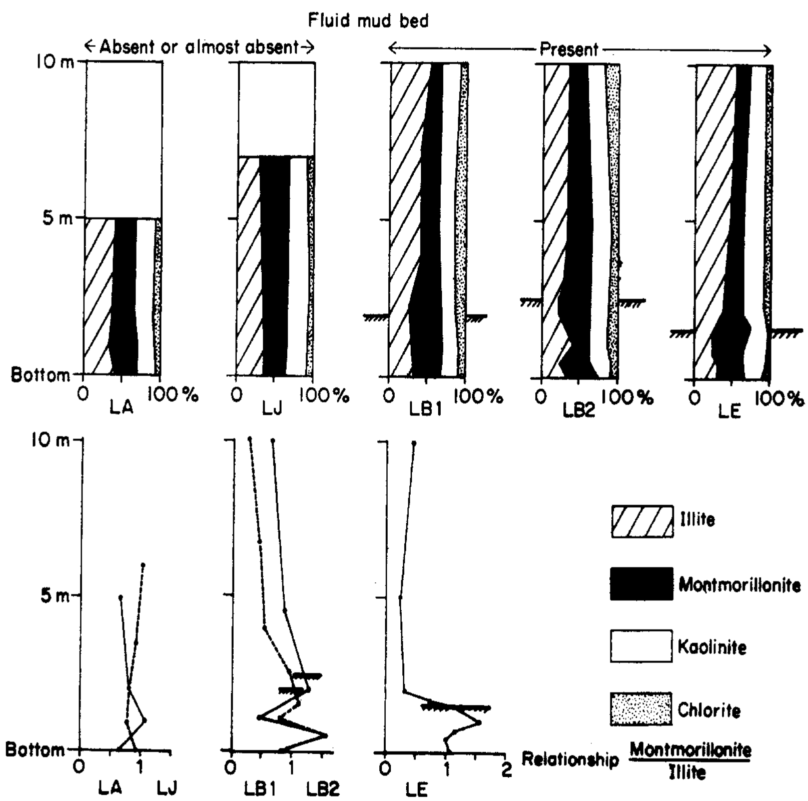

Figure 4. Vertical variation in argillaceous minerals.

Kaolinite is not subject to any vertical variation which confirms its homogeneity over the whole water section;

Chlorite is also constant but its percentage is too low (5–10%) for it to be analysed in detail;

Illite and Montmorillonite behave quite differently. At a level with the top of the fluid mud, that is to say in the transition zone between the turbidity maximum and the fluid mud, there was a significant concentration of Montmorillonite. The variations in the percentage of Montmorillonite are in inverse proportion to the variations in the percentage of Illite.

This concentration of Montmorillonite can be explained by differential settling rate. In effect, the Montmorillonite has a very small quantity and a very low speed of sedimentation (2×10^{-3} cm/s), whereas that of the Illite is around 18×10^{-3} cm/s for a salinity of 10‰ (Meade, 1970; Postma, 1967; Whitehouse *et al.*, 1958). It is, therefore, logical to find the Montmorillonite in the upper part of the fluid mud whereas the Illite is incorporated within the fluid mud itself.

However, the transformation hypothesis should also be examined. Montmorillonite–Illite type transformations due to cation exchange in the open sea have been described by a number of authors (Grim & Johns, 1954; Millot, 1964; Cailleres & Herin, 1963). The upper part of the fluid mud where, as we have seen, a significant salt diffusion exists, could be the centre of such transformations which we did not have the means to study.

Longitudinal displacement of the silt sludge. We have seen that it is possible to follow the longitudinal displacement of the fluid mud from season to season and as a function of the flow of the Loire. During 1972, we tracked this variation by sounder recordings (Figure 5). On those occasions when the fluid mud could not be detected (high tide coefficient, tide time not propitious), we assessed its position as a function of the flow and on the basis of earlier observations.

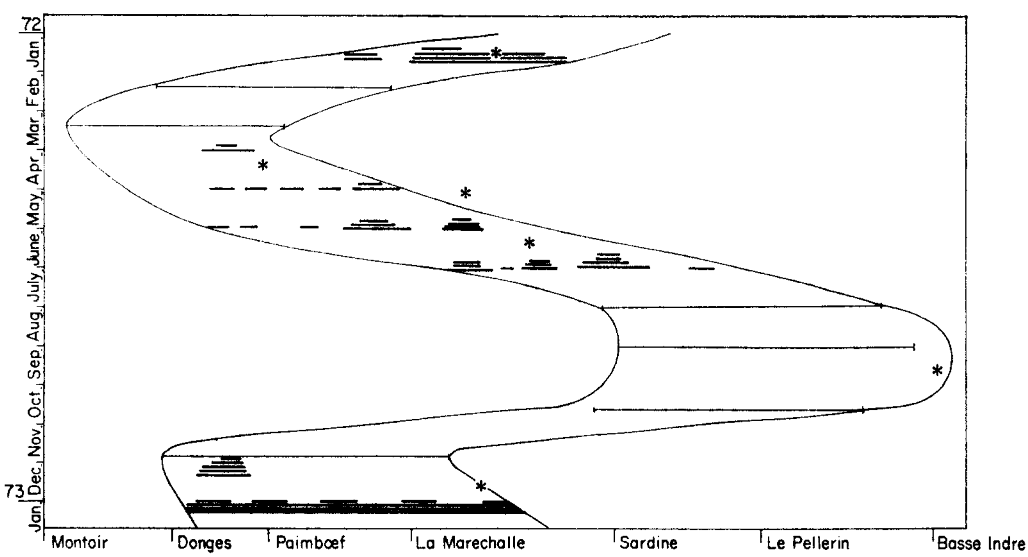

Figure 5. Longitudinal variations in the fluid mud and Montmorillonite. ——, fluid mud by ultrasonic depth sounding; |——|, fluid mud estimated statistically or by other observers; *, position of maximum observed concentration of Montmorillonite.

The seasonal shifting of the fluid mud is easily detected, during high water it is expelled downstream, whereas in low water it moves upstream as far up as Basse-Indre.

Longitudinal displacement of the maximum percentage of Montmorillonite. We have seen that the distribution of Montmorillonite in the suspended sediments is in the form of an inverted curve with its maximum concentration in the middle of the estuary. We were able to follow the seasonal displacement of these maxima of Montmorillonite from the longitudinal samples taken at various times as shown in Figure 5.

It should be noted that maxima of Montmorillonite are, in general, to be found in the upstream part of the fluid mud. This is in agreement with the hypothesis of dynamic selection due to the small size and low speed of sedimentation. The finest particles, like Montmorillonite, move more slowly in suspension in the vertical direction and in the longitudinal direction.

With the aid of the vertical and longitudinal samples, we have seen that there is a significant concentration of Montmorillonite at the level of the fluid mud. This concentration is particularly great at a level with the top of the fluid mud, in the upstream sector. The transfer back into suspension of this intermediate zone, which is rich in Montmorillonite, brings about the relationship between Montmorillonite and the turbidity maximum.

Relationship between Montmorillonite and the turbidity maximum

Variations in the percentage of Montmorillonite were tracked by taking samples from the turbidity maximum over a period of 13 hours at fixed points in two regions of the Loire estuary, downstream near St. Nazaire and upstream near Nantes.

Figure 6 shows the variations in turbidity, salinity and percentage of Montmorillonite during a single tide in the region of St. Nazaire. The passage of the turbidity maximum was registered twice and is indicated by the two maxima in turbidity:

at the end of the ebb tide the turbidity maximum is expelled towards the open sea (900 mg/l or turbidity);

at mid-tide only a small part of the turbidity maximum moves upstream (90–110 mg/l of turbidity);

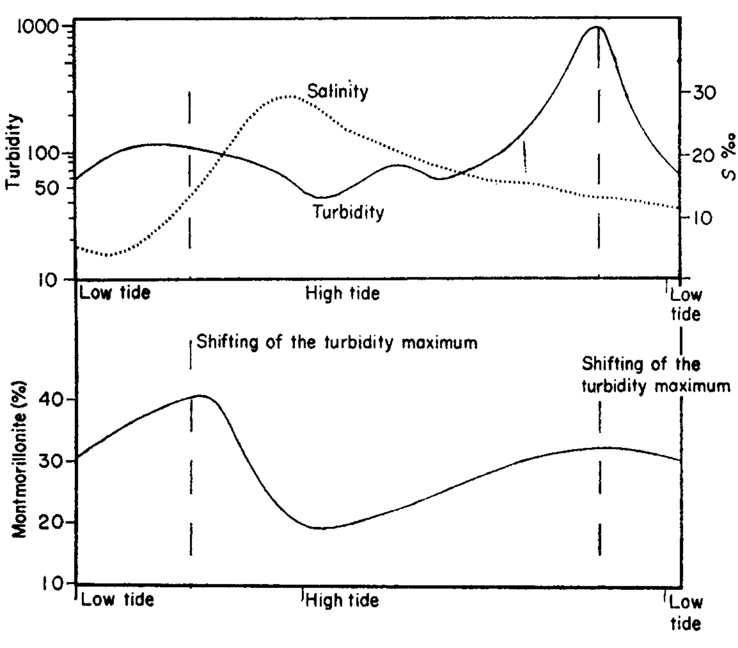

Figure 6. Relationship between Montmorillonite, salinity and turbidity during the course of a single tide.

in the open sea, turbidity does not exceed 40 mg/l. As the turbidity maximum has gone upstream in the estuary, more than the weak turbidity of the sea water is registered.

The percentage of Montmorillonite follows, quite closely, the variations in turbidity associated with the presence of the turbidity maximum.

At ebb tide, whilst the turbidity maximum is passing downstream, high percentages of Montmorillonite (30%) are registered, and at high tide, during its return, the percentages are even greater (40%). This relative increase in Montmorillonite can be explained by differential sedimentation due to contact with salt water. According to the hypothesis put forward by Whitehouse *et al.* (1958) there should be a premature deposition of Illite whereas the Montmorillonite remains perpetually in suspension.

At high tide, the turbidity maximum, now enriched with Montmorillonite, is re-injected upstream and the lowest percentages of Montmorillonite are recorded in the open sea.

During the whole low water period in 1972, samples were taken in the Nantes approaches over the whole 15 days at low tide and in the middle of the channel, using the laboratory's Zodiac, upstream (Pont de Bellevue) and downstream (Cale de Basse-Indre). The results of these samples are given in Figure 7.

Measurements of turbidity taken in June/July, at the start of the low water, gave values of 20–30 mg/l in the upstream sector and 30–40 mg/l in the downstream sector. This increase is due to drainage from the town of Nantes before the turbidity maximum is again located in the estuary. In the middle of the low-water period (September), turbidity is around 90 mg/l in the downstream sector and around 50 mg/l in the upstream sector. This demonstrates that the turbidity maximum has moved upstream as far as Nantes and, basically, is located in the port and in the downstream part of Nantes.

At the end of the low-water period, very high turbidity values are noted. In October, it is at its maximum of 100 mg/l in the upstream sector, whereas in the downstream sector it is not more than 40 mg/l. The turbidity maximum has therefore passed Nantes and is located upstream where it is opposite the town's water intakes with all the difficulties for study that this entails.

In November, turbidity becomes high again in the downstream sector, 180–300 mg/l as opposed to 50 mg/l upstream. This clearly shows the persistency of the turbidity maximum in the lower part of the port of Nantes. In December, in line with the increase in the flow of the Loire; turbidity becomes normal again (30 mg/l) and the turbidity maximum begins, again, to descend towards the estuary.

In May, 1972, in average flow conditions, Montmorillonite was rare at Bellevue (upstream) and had a value of 15–20% at Basse-Indre (downstream), on either side of Nantes. During low river discharge, June–September, the upstream percentage was 10–20% whereas downstream it was 25–35%. The largest percentages were noted at the end of the low discharge period, October–November: 25–30% upstream, 30–40% downstream. The return to normal flow conditions >800 m^3 (December) brought about a fall in the percentage of Montmorillonite: 15% in the upstream and 20% in the downstream.

These observations were further confirmed by analysis of three longitudinal readings in the Summer of 1972 which showed a maximum of Montmorillonite to be located in the interior of the estuary, with a considerably diminished percentage upstream (0–20% in the region of Nantes), and downstream (15–20% in the region of St. Nazaire). Furthermore, an upstream displacement on Montmorillonite was observed during low discharge which accompanied that of the turbidity maximum.

The variations in Montmorillonite can be considered an analogous to those in turbidity. It is in particular at the end of low discharge that turbidity and the percentage of Montmorillonite are at their greatest. In these cases, the increase in Montmorillonite, as with turbidity, observed in the port of Nantes at low water, is brought about by the increase in the quantity of clays, concentrated in the estuary, through the transport process of the turbidity maximum.

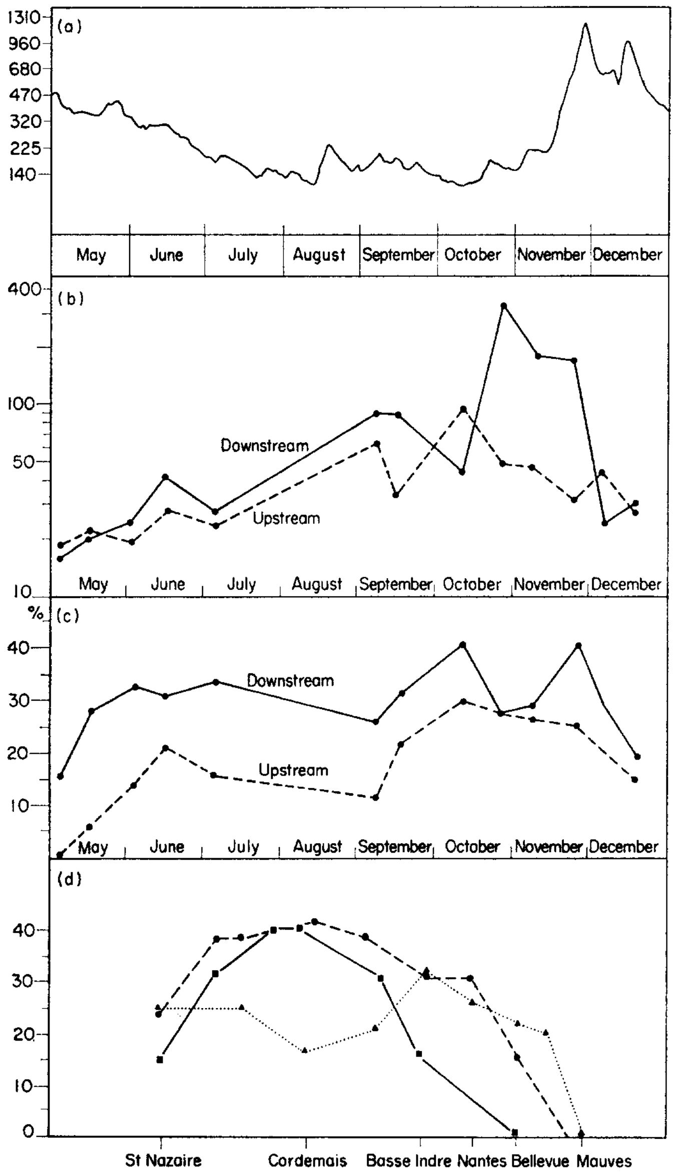

Figure 7. Variations in the percentages of Montmorillonite in relation to turbidity and flow in the Loire. (a) Flow in the Loire (m^3/s), (b) turbidity in the region of Nantes (mg/l), (c) Montmorillonite in the region of Nantes (%) and (d) Longitudinal variations in Montmorillonite (%). In (d) symbols are: —■—■—, 3 May; —●—●— 14 June; - - -▲- - -▲- - -, 14 September.

The Montmorillonite can therefore be used to trace the movement of the turbidity maximum as well as confirming that the variations in turbidity, observed in the port of Nantes after a prolonged low-water, are due entirely to its transport upstream and not to local agitation (drainage, river works, dredging, etc.).

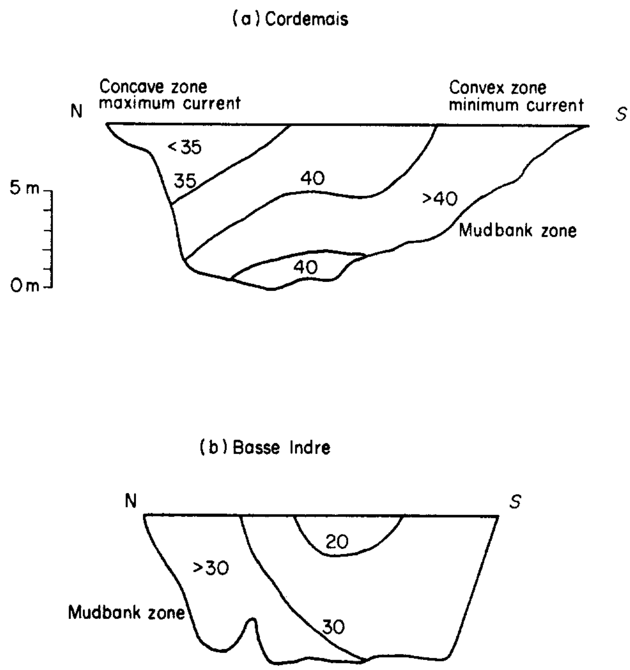

Figure 8. Lateral variations in the percentages of Montmorillonite in suspended argillaceous minerals in two transverse profiles of the Loire. (a) Fluid mud present, (b) Fluid mud absent.

Relationship between Montmorillonite and lateral deposits

Transverse samples, from the bottom and from the suspension, taken from the estuary (Figure 8) provide complementary information on the distribution of Montmorillonite.

At Cordemais, it was in fact established, as earlier, that a concentration of Montmorillonite at a level with the top of the fluid mud and on the lateral mudbanks of the riverside is connected with the point of weakest current. From the bottom samples one also found a percentage of Montmorillonite higher on the banks and the side mudbanks than in the bottom of the central channel which had already been established in the Gironde (Latouche, 1971). This relative richness in Montmorillonite on the side mudbanks can be explained by the trapping of the Montmorillonite in accordance with the accretion phenomena (Glangeaud, 1938, 1941; Berthois, 1954).

Conclusion

The preceding analysis confirms the presence, in the estuary, of a concentration of Montmorillonite in the suspended sediments. This stock of Montmorillonite occurs, due to dynamic causes, at a higher level than the fluid mud.

Given the constant exchanges which take place between the fluid mud, the turbidity maximum and the side mudbanks it is of interest to follow the variations in the maximum percentages of Montmorillonite in the interior of these formations during their displacement or their successive build-ups. The stock of clays, rich in Montmorillonite, is, in effect, constantly recycled into the interior of the estuary by the mechanism of the turbidity maximum/fluid mud/side mudbanks system. Detailed analysis of the behaviour of Montmorillonite show that it can be used as a natural indicator of the sediments in the estuary.

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