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Nature and rates of fine-sedimentation on a mid-shelf: "La Grande Vasière" (Bay of Biscay, France).

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Abstract:

The study area, "La Grande Vasière" (LGV), stretches out on the French Atlantic continental shelf (at ca. 100m water depth), along 250 km from the Glénan Islands at the north to the southwest of Rochebonne at the south. Box-cores were sampled in this mid-shelf area during four cruises in June 1995, and in April, June and September 2002. They were investigated using sedimentological approaches (X-radiographs and grain-size analyses) and radionuclide studies (210Pb geochronology and excess 234Th). The main results are: (1) the surficial sediments are generally organized into a decimetre-scale fining up sequence which can be the result of extreme storms; (2) an upper mixing layer of 7-20 cm reflects an important biological benthic activity and/or the impact of fishing (i.e. trawlers); (3) a thin (i.e. a few mm) surficial mud-rich layer is the result of the present-day sedimentation; (4) an apparent annual sedimentation rate of 1- 3 mm is recorded in several loci of the study area. Some seasonal variations appear, corresponding to the deposition of fine material from April to September, and to the reworking and the re-suspension during the winter. This fine material is the result of the decantation of estuarine plumes, mainly the Loire and the Vilaine rivers, over the study area. LGV lies (1) under the influence of a winter-to-spring thermo-haline wedge that acts as a filter for the transfer of fine river-borne material to the slope and the open sea, and (2) below water depths where the mean swell action permits sedimentation, mainly in summer. From the point of view of the nature of its sediments, LGV is not a mud-belt, but a heterolithic and patchy sandy area that is submitted to increasing silting with environmental changes, on a seasonal-time scale.

Keywords: Mud, fine-sediment fraction, radionuclides, sedimentation rate, continental shelf, Bay of Biscay.

1. Introduction

In order to better understand biogeochemical cycles, the transfer of contaminants and the formation of strata, a number of recent and extensive studies were focused on the transfer and the accumulation of fine-sediments on continental margins. These margins are an essential link between the land and the oceans (e.g. Milliman et al., 1972; Nittrouer and Wright, 1994; Wright and Nittrouer, 1995; Wheatcroft et al., 1997).

Typical of the European Atlantic shelf, the Bay of Biscay is an overall sand and gravel covering resulting from the pre-Holocene and Holocene periods. During the last decades, the southern part of the shelf, in front of the Gironde estuary, has been the focus of lithological and sedimentological studies (e.g. Jouanneau et al., 1999; Lesueur et al., 2001; Jouanneau et al., 2002; Lesueur et al., 2003). However, there was a gap of information about the knowledge on fine-sedimentation over the northern part in the Bay of Biscay continental mid-shelf. This area is known as La Grande Vasière (LGV), i.e. “The Great Mud field”.

LGV is a muddy area, situated in water of around 100 m depth, and stretches out along the shelf for more than 250 km, from the Bay of Audierne (at the northwest), to the Rochebonne shoal (at the southeast), and is about 30 km wide (Fig. 1). Known since the end of the 19th century (Delesse, 1871) it has been described as a thin and broken blanket of mud overlying ill-sorted coarse-grained sediments (Berthois, 1955; Berthois and Le Calvez, 1959). Others studies showed that mud was found especially in morphological traps in the northern part of the mid-shelf (Pinot, 1966). The content of the sediments in the sediments in LGV are about 20% silt+clay (Vanney, 1969), or are considered as muddy sands with 25% silt+clay content (Pinot, 1974).

The extension of this mid-shelf muddy area is also variable, as its surface area could be halved in winter conditions (Pinot, 1976).

A synthesis of several works led Allen and Castaing (1977) to draw a map of LGV, in its maximal extension (Fig. 1). Recent work has showed that LGV accounts for about 75 % of the surface area of muddy sediments on the French Atlantic shelf (Jouanneau et al., 1999).

From these observations, some questions arise: (1) Are there many differences in the fine sedimentation at the scale of the whole muddy area? (2) What are the sedimentation rates in LGV? (3) Is this muddy area really susceptible to seasonal variations?

2. Environmental setting

2.1. Geomorphology and sediments of the shelf

LGV stretches out on the middle third of the French continental mid-shelf, in water depths between 70/90m and 110/120m, on a surface that dips gently to the southwest (1:1000 average gradient). It corresponds to a reasonably flat region, but presents a diversified topography marked by low relief of sands, gravels and weakly buried rocks toward the inner shelf. As a whole, the substratum of the mud blanket is composed of heterogeneous palimpsest sands and shelly gravels derived from fluvial deposits, that were reworked and mixed with a variable part of marine shell debris during the Holocene transgression. Fine sands cover the outer-to-mid shelf, while medium and coarse sands make up the cover of the middle-to-inner shelf in the northern Bay of Biscay (Allen and Castaing, 1977). There is evidence of several scarcely integrated drown valley networks being slightly reworked in a period of low sea level (Vanney, 1977). Due to its location on the middle shelf and to the presence of some offshore bars of gravel and cobbles at its outer border, LGV had been considered for a long time to result from offshore or even lagoonal deposits, during a period of low sea level (Bourcart, 1947; Berthois, 1955). More recently, this discontinuous mud-rich area was assumed to be a result of only present-day sediment supplies (Pinot, 1974), or as relict Holocene deposits (i.e. paleo-estuarine sediments settled during a lower sea level) but also supplied with modern fine sediment (Vanney, 1977).

2.2. Currents and waves on the continental shelf

Residual currents over the shelf of the Bay of Biscay are principally governed by winds, tides and density-driven circulation (Vincent and Kurc, 1969; Pingree and Le Cann, 1989; Le Cann, 1990). Over the southern Brittany shelf, the residual currents remain weak (about 3 cm s^{-1}), and are oriented towards the northwest. In the south, over the Aquitaine shelf, the residual circulation shows a marked seasonal character mainly due to the seasonal dynamics of the dominant winds. Although general currents are not strong enough to remove the sediments, they control the extension of the surface estuarine plumes. Remote sensing imagery and numerical models (Lazure and Jegou, 1998; Castaing et al., 1999) show that at the beginning of winter, the plumes spread out northward, but remain over the inner shelf. Contrary to this in spring, winds are from the northwest to the southeast, and the plumes are stopped. Then, they are directed towards the shelf break or are pushed back towards the south. Effects of tidal currents are weak on the middle shelf: maximum velocities do not exceed 10 to 15 cm s^{-1} even at the surface (Castaing, 1981).

The Bay of Biscay is a storm-dominated shelf (Arbouille, 1987; Weber et al., 1987). The swell during storm events are able to move the sediments on the mid-shelf. According to the nature of the sediments, Castaing (1981) claimed that a swell with a period of 12 s and an amplitude of 6 m, can move a particle of 100 µm at 100 m water depth, but such conditions only occur once each year. The estimations showed that long-period (15 s) and very high amplitude (20 m) swells generated by winter gales are capable of stirring the bottom sediments on the entire shelf; however, these conditions occur in water depths >80 m only for periods less than 12 hours in a year (Castaing, 1981; Barthe and Castaing, 1989).

2.3. Fluvial sources

Rivers are the main sources of fine sediments to the Bay of Biscay. The main rivers that deliver suspended matter are, from the north to the south (Jouanneau et al., 1999): the Vilaine river (0.1 x 10^6 t $year^{-1}$), the Loire river (0.5-0.6 x 10^6 t $year^{-1}$), the Charente river (0.1 x 10^6 t $year^{-1}$) and the Gironde estuary (1.5 x 10^6 t $year^{-1}$). The fine sediment fluxes from the remaining small rivers of south Brittany are poorly known but can be estimated to be very low.

3. Methods

Several sets of box cores, with a maximum length of 15 to 35 cm, were collected during four cruises. One cruise was in June 1995 (DEPOVASE cruise) in the southern part of LGV from Rochebonne to the west of Yeu Island and the other three cruises were in 2002 in the northern part of LGV (Fig. 2). The latter cruises took place in April-May 2002 (GASPROD cruise) and September 2002 (TROPHAL 2 cruise).

Box cores were opened and aluminium slabs then pushed to the open half core and extracted. Radiographical analysis of all cores was performed. The cores sampled in 2002 were analyzed with X-ray equipment (SCOPIX ®) coupled with radioscopy instrumentation and processing (Migeon et al., 1998). As the gray-scale intensity of the X-ray image was considered to be a function of the sediment density, it was used to select the sampling of the layers for grain-size analysis.

The relatively finer sediments (<650 µm) of the cores were analysed for grain-size distribution with a Mastersizer S laser dffractometer (Malvern Instruments). The more coarse-grained layers were analyzed with a series of sieves (5 mm / 3.15 mm / 2 mm / 1.25 mm / 0.8 mm / 0.63 mm / 0.5 mm / 0.4 mm / 0.315 mm / 0.25 mm / 0.2 mm/ 0.16 mm/ 0.125 mm/ 0.1 mm/ 0.063 mm). Furthermore, after drying, the sediment was washed on a sieve ϕ=63 µm to separate the fine-sediment fraction.

Radioisotopic measurements were made using a semi-planar germanium detector (EGSP 2200-25-R from EURYSIS Measures) coupled to a multichannel (8000 channels) analyser. Samples were chosen after examination of X-ray images of the cores, except for the uppermost sediment layer which were processed directly aboard for ^{234}Th counting purposes. Dry homogenized samples were packed in 9.5 ml sealed Petri dishes. Radioisotope activity concentrations were calculated by multiplying the counts per minute by a factor that incorporates the gamma ray intensity and detector efficiency.

^{210}Pb activity concentrations were determined by direct measurement of its gamma decay energy at 46.5 KeV and corrected to the sampling date. Excess ^{210}Pb ($^{210}Pb_{exc}$) was calculated from the ^{210}Pb activity by subtracting the average of two ^{214}Pb energies (295.2 KeV and 352.0 KeV), and a ^{214}Bi peak at 609.3 KeV which represents the ^{226}Ra activity and corresponds to the supported ^{210}Pb. When the $^{210}Pb_{exc}$ profile decreases with depth, this natural radionuclide allows estimation of sedimentation rates during at

least the past century due to its 22.3 yr half life (e.g. Koide et al., 1972; Nittrouer et al., 1979).
^{234}Th ($t_{1/2}$ = 24 days) is another naturally occurring radionuclide that permits scientists to examine mechanisms of sediment dispersal and deposition on a 100-day time scale (e.g. DeMaster et al., 1985). Excess ^{234}Th ($^{234}Th_{exc}$) was calculated after subtraction of the estimated supported ^{234}Th from the activities of ^{214}Pb (295.6 and 352 keV) and ^{214}Bi (608.6 keV). The supported ^{234}Th corresponding to the “father “ of ^{234}Th: ^{238}U.
Sampling was made on board, and radioisotope analysis was conducted 3-7 days after sampling and corrected to the sampling date. Other analyses were performed on the same samples after more than 100 days (>5 half lives of ^{234}Th) and corrected to the same sampling date. For instance, the first $^{234}Th_{exc}$ analyses on a sample of GAS_G (level: 0.5-1 cm) displayed an activity of 103.6 ± 13 Bq kg^{-1} but their repetition (second analyses four years later) an activity of 8 ± 13 Bq kg^{-1}. $^{234}Th_{exc}$ in the sample TRO2_G (level: 0-0.5 cm) decreased from 196.1 ± 20 Bq kg^{-1} (first analyses) to 0 ± 12 Bq kg^{-1} (second analyses). These new results gave a satisfactory answer, as largely more than the 5 periods recommended after, no significant $^{234}Th_{exc}$ was found. So, results concerning evidence of $^{234}Th_{exc}$ in surficial layers of some stations are not arguable: this excess is the result of process of seasonal settling.
An other way to estimate this excess is to investigate downcore the sediment layers until a rather constant ^{234}Th activity was reached, which was considered as the supported activity. This rougher method gives however a good and easy information, as the gamma analysis covers the range from 30 keV to 1800 keV: all the different peaks are measured at the same time.

To take into account the influence of the variations in the grain-size in the results of ^{210}Pb analyses, $^{210}Pb_{exc}$ and $^{234}Th_{exc}$ measured activities were normalized relative to the fine-sediment content (%< 63 □m).

$$^{210}Pb_{exc\ norm} = {}^{210}Pb_{exc} / (\%< 63\ \mu m) \times 100$$
$$^{234}Th_{exc\ norm} = {}^{234}Th_{exc} / (\%< 63\ \mu m) \times 100$$

4. Results

4.1. Grain-size of surficial sediments

Analyses of surficial sediments led to the definition of the different classes of grain-size and characteristic statistical parameters (i.e. median grain diameter, mean grain size, different modes). According to the geography and the sedimentology (lithology, grain-size, fine-sediment content) of the surficial sediments during the cruises, the cores were divided into several sets (Table 1, Table 2):
- **station G** in the northern zone with a very high fine-sediment content (88-92 % < 63 □m) and with a mean grain diameter of 15 µm,
- **central zone,** around 100 m water depth, of very fine sands (stations A, B, C, D, H, I, J), with a mean grain diameter at 70-190 µm, the fine-sediment content remaining lower, at 11-42 % with an average value of 25 %,

- **station K** at a similar water depth (94 m) but in the most southern area in Rochebonne hole, is more muddy, with a mean grain diameter around 10-18 µm,
- **station E,** on the outer shelf at the deeper boundary of LGV, where sandy sediments were found (mean grain diameter: 220 µm), with a very low content of fine sediment (around 5 %).

As a general rule, with the exception of the stations G and K, mud was thus of secondary importance, while fine sands (125-250 µm) made up the most important component of the sediment in the whole area of LGV (Table I).

4.2. Lithology of selected cores

No physical structures (i.e. erosive surfaces, laminae of fine-sediments) were clearly observed; if present, they had not been preserved and could have been masked by the intense mixing. In fact, burrows of various shapes were obvious on the X-ray images all along the cores.

Four cores were investigated for this paper: GAS_G (station G), GAS_CC2 (station C), TRO2_E3 (station E) and KI_95136, as being representative of various geographical zones of LGV (Fig. 3, Fig. 4).

The **GAS_G** core is composed of a silty mud, with a mean grain diameter of 12-16 µm. Shell remains dominate at the lower part of the core (20-27 cm), which displays at its top a thin fluid mud layer, ~2 cm thick. The latter was very obvious during the sampling on board. X-ray images do not show any physical structures, except for isolated burrows. The sediment was very homogeneous due to mixing (Fig. 3A).

The **GAS_CC2** core is composed of very fine sands with a mean grain-size of 50-130 µm. This core displays some horizontal and circular burrows between 5 and 15 cm sediment depth and shell remains at the bottom of the core (15-24 cm). There is also a thin mud layer ~5 mm thick at the top of the core, but there is not any physical structure recognizable on the X-ray image (Fig. 3A).

The **TRO2_E3** core is made of medium to fine shelly sands with a mean grain diameter of 200-320 µm. This core is burrowed, and shell debris appears at 5-24 cm, with increasing amounts and a resulting increasing-grain size with sediment depth. X-ray imagery does not display any sedimentary structures, except from shelly remains. A thin mud layer, about 5mm-thick, forms the top of the core. Although this core was sampled beyond the limits of LGV (according to the map by Allen and Castaing, 1977), it is representative of most of the cores that display a general tendency of finer material towards the sediment surface (Fig. 3B).

The **KI_95136** core is made up silty fine sands with a mean grain-size of 10-20 µm. Subtle horizontal burrows and tracks are obvious on the X-ray image, with distinct sand-infilled burrows at the base. A surface mixed layer extends down to a depth of 9 cm (Fig. 4).

To sum up, the cores sampled in LGV display, whatever the sampling period, a thin (i.e. a few mm to 2 cm) surface mud-rich layer. This fine surface layer was observed in most stations, having no temporal relationship with when samples were collected. As a whole, sediments are strongly mottled, due to mixing by burrowing and tracking (i.e. horizontal, vertical and oblique burrows) on the upper ten to fifteen cm of the cores. A large part of the sediment is composed of sand, shells and shelly debris, with a decreasing occurrence towards the top of the cores. In the areas of the two ends of LGV, i.e. the northern station and the southern stations, the mud content is high. Apart from these two areas, the grain size gradually decreases upward in the 20-30 cm surficial sediments. The result is a fining upward sedimentary sequence of sands, whatever the location in the central zone.

4.3. Radioisotopes activities and profiles

Generally, based on the ^{210}Pb and the ^{234}Th data, the thickness of a surface-mixed layer (SML) and sedimentation rates can be estimated (e.g. Guinasso and Shink, 1975; Nittrouer et al., 1979).

In many of the studied cores, the profiles of ^{210}Pb and ^{234}Th do not show evidence of a decrease with depth; this is probably due to a thick mixed layer, about 20 cm thick or more (Fig. 5). Only four cores were used to estimate accumulation rates (Fig. 5). The remaining cores were not used because of their strong bioturbation (evident on the X-Ray images) that would strongly disturb the results. However, the excess ^{210}Pb profiles have led to “apparent sedimentation rates”, that should be considered as maximum accumulation rates based on negligible mixing below the surface mixed layer (Nittrouer et al., 1984-85).

In the **core GAS_G** (station G) sampled in the northern part of LGV, the excess ^{210}Pb suggests a logarithmic decrease, from 10 to 26 cm sediment depth (Fig. 5) below a SML. The apparent sedimentation rate is estimated to be 0.29 cm yr^{-1}. The $^{234}Th_{exc}$ profile shows a decrease (196 to 29 Bq kg^{-1}) on the upper two cm of the core.

The cores GAS-CC2, GAS-DD1, GAS-B2 and KI were sampled in the central zone. The profile of $^{210}Pb_{exc}$ along the core **GAS_CC2** (station C) does not exhibit a decreasing tendency. However, $^{234}Th_{exc}$ slightly decreases from 45 to 21 Bq kg^{-1} with depth along the upper 3 cm. In the core **GAS-DD1** (station D, silty sand), the accumulation rate is estimated to be 0.16 cm yr^{-1} between 5 and 11 cm sediment depth, below the SML (Fig. 5). The accumulation rate in the core **TRO2_B2** (station B, silty sand), as estimated between 7 and 13 cm below the top, is approximately the same: 0.19 cm yr^{-1} (Fig. 5).

The core **TRO2_E3** (station E) was sampled in the northern outer shelf, outside the muddy area of LGV. Below a SML of about 7 cm, there is a slight decrease with depth in the $^{210}Pb_{exc}$ profile along the topmost 21 cm (Fig. 5). However in this case, it can be due to the strong downward increasing grain-size tied to the increasing coarse shell debris; as a result, no rate was accepted for this core. There is a thin surface mud layer, 0.5 cm thick, and the $^{234}Th_{exc}$ profile decreases slowly along the topmost three cm of the core (46 to 10 Bq kg^{-1}).

The core **KI_95136** (station K) was sampled in the Rochebonne hole. A surface mixed layer, where $^{210}Pb_{exc}$ activity remains constant extends down to a depth of 9 cm, and then a slight decrease occurs. The sedimentation rate is calculated to be 0.22 cm yr^{-1} at this station.

4.4. Variations of grain-size and of radionuclides activities with time

Replicate sampling of surficial sediments on some stations but during different seasonal conditions showed minor differences during the study in 2002. A general increase in the fine-sediment content was recorded, from spring (April 2002, GASPROD cruise) to summer conditions (September 2002, TROPHAL 2 cruise). The difference is generally more pronounced at the stations of the central zone than in station G, where the fine-sediment content is higher (Table 2).

In 2002, the geographic distribution of $^{210}Pb_{exc}$ activities, as measured at the top of the studied cores and relative to the fine-sediment content (Table 2), shows higher values on the more northern stations of the muddy area (stations A, C, G) and in the outer station (station E), than on the more southern of LGV (stations B and D): 40-200 Bq kg^{-1} at the first locations *versus* 13-68 Bq kg^{-1} at the second ones. Replicate sampling and analyses of excess ^{210}Pb on same station showed an increase in the activity between spring and summer in 2002 (values < 100 Bq.kg^{-1} in April and 59-250 Bq kg^{-1} in September).

$^{234}Th_{exc}$ activities in the surface layer of sediments in 2002 (Table 2) were also higher in the northern part of the study area (stations A, C and G) than in the more southern locations (stations B and D). $^{234}Th_{exc}$ inventories were estimated in the three upper cm of some cores, taking into account the dry density of the sediment (Table 3). The maximum $^{234}Th_{exc}$ inventories were found to correspond to the summer cruise in the north, at station G (>151 mBq, TRO2_G) and then at station C (>102 mBq, TRO2_C). Conversely, the inventories were lower: (1) in summer at the stations E (60 mBq, TRO2_E) and B (31 mBq, TRO2_C), and (2) in spring at the station C (61 mBq, GAS_CC2).

5. Discussion

5.1. General findings

All authors agree that the mid-shelf muddy area lying on the mid-shelf and known as LGV is in fact a patchwork of ill-sorted sands, in which the entrapped fine-sediment material may account for a mean of 25 % the total dry mass of the sediment (Berthois and Le Calvez, 1959; Pinot, 1974; Vanney, 1977; Lesueur et al., 2001). The central zone, as defined in this study, is representative of this average value (25 % fine-sediment fraction), while three stations of the study area are strongly distinct: (1) the more coastal and northern station (98 m water depth), with a very high content in mud; (2) the outer and deeper sandy station (138 m water depth, station E) and (3) the southern station near Rochebonne shoal (94 m) where mud is likely to accumulate.

The lithological data of the surficial sediments obtained on most of the cores sampled in 2002 are very similar to those from other surficial cores sampled in 1995 in the southern area of LGV between the west of Yeu Island and Rochebonne shoal, at ca. 100 m water depths (cores KI_95144, KI_95142 and KI_95140, Fig. 4). In the two sets of samples, deposits are organized into a decimetre-scale fining upward sedimentary sequence, from coarse or medium shelly sands to fine muddy sands, and then a very thin (a few mm) fine-sediment surficial layer. More or less pronounced depending on the location, this fining upward tendency seems thus to be a general rule in the wider part of LGV. This feature should be compared to other sequences described both in ancient and modern storm-dominated deposits. In particular, analogous sequences described on the southern part of the continental shelf of the Bay of Biscay have been attributed to storms, both in sands (Arbouille et al., 1987) and in fine sediments (Lesueur et al., 2003).

Based on excess ^{210}Pb, the estimated sedimentation rates during, at least the last century, range between 0.21 and 0.26 cm yr^{-1}. These are high values for an open shelf area far away (i.e. >100 km) from any source of fluvial fine-sediment supplies. However, these rates are of the same magnitude than those based on cores collected at about 100 m water depths in the southern area of LGV (0.22-0.26 cm yr^{-1}) and, on the same shelf, in the wider part of the Gironde inner shelf mud fields (0.1-0.5 cm yr^{-1}, Lesueur et al., 2001, 2003).

Other estimations of excess ^{210}Pb accumulation rates on the Atlantic European shelf were found to be rather variable (see a review in Lesueur et al., 2001): on the Atlantic Iberian shelf they are found to vary between 0.05 and 0.4 cm yr^{-1} (Dias et al., 2002; Jouanneau et al., 2002). They are statistically in the order of magnitude of 0.2 cm yr^{-1} over the whole European Atlantic muddy shelf (Jouanneau et al., 2000), of 0.1-0.3 cm yr^{-1} on the Valencia shelf in Spain (Nittrouer et al., 1985). The accumulation rates are of 0.1-0.24 cm yr^{-1} on the northern California shelf (Demirpolat, 1991; Leithold, 1989), but they increase to 0.3-0.7 cm yr^{-1} on the Washington shelf (Nittrouer et al., 1979) in relation with the higher fluvial fluxes.

5.2. Origins of the mixed layer and modern fine-grained deposit

5.2.1. Mixed layer

Of the superficial sediments studied here, there is no evidence of internal primary physical structures such as thin individual laminae, discontinuities in sedimentation or erosive contacts, analogous to those that have been described in other shelf mud field deposits in the Bay of Biscay, as in front of the Gironde estuary (Lesueur and Tastet, 1994). Contrarily, a strong mixing is obvious on X-ray images from the studied cores, and a surface mixed layer of 7-20 cm-thick is revealed by the homogeneous values of excess ^{210}Pb at the top of all analyzed cores. The causes of the mixing need to be investigated.

Due to the weakness of the currents on the middle shelf, Castaing (1981) estimated that currents could never remove the sediments of LGV, neither general currents, nor tidal currents, but only by storm swells. In such a context of heterolithic surficial sediments, rare but strong storm events could be recorded in cores, as storm-graded layers deposited on erosive contacts as on the well-studied Aquitaine shelf (e.g. Arbouille et al., 1987; Lesueur and Tastet, 1994).

Furthermore, various investigations on the whole Bay of Biscay shelf (Lazure and Jegou, 1998; Castaing et al., 1999; Jouanneau et al., 1999) have shown that the study area can be under the influence of estuarine plumes (e. g. Loire and Vilaine rivers). Thus, thin laminae of mud can be observed (e.g. using RX-ray methods) within the deposits, as a result of the settlement of fine-sediment fluvial discharges but they are not, as they are mixed within the coarse sediments.

Mixed layers in shelf sediments can have different origins: (1) a strong biological reworking by benthic fauna, or (2) impacts of trawl fishing on surface sediments, or (3) the consequence of both. The influence of storms cannot be excluded from the mixing processes, but unfortunately no stratification can be observed on X-radiography images of box cores. The biological activity can be revealed by the presence of many shell remains (gastropods and bivalves, *Dentalium*), and various diffuse bioturbation structures. Nevertheless, with strong mixing, isolated traces are perceptible: they include vertical and horizontal burrows, probably due to polychaetes, gastropods and bivalves, and circular tracks (“press structures”) due to echinoderms (Glemarec, 1969).

The influence of anthropological reworking of sediments by fishing can not be quantified. Bottom trawlers are known to be the more frequent fishing practice on the Bay of Biscay shelf, particularly in summer between the coast and the 100-150 m water depth (Léauté, 1998). This is the area where the LGV extends to. According to IFREMER, the geographic zone (Fig. 6) that corresponds to the central zone (in particular stations A and C) is the most important fishing area, compared to other zones as those that correspond to stations B and D. Different kinds of impacts from trawlers can be considered (e.g. Lesueur and Tastet, 1994): (1) narrow (i.e. a few m) traces of otter boards with penetration up to a few tens of centimetres deep in soft sediments, and (2) wide (i.e. tens of m) ground-net tracks, a few cm deep. However, to quantify the impacts of commercial fishing activities on surficial sediments of modern shelves is very difficult; then they are widely underestimated in comparison with biological reworking (Hoffmann et al., 1990).

5.2.2. Modern fine-sediment deposition

A mud-rich layer is commonly observed at the top of the cores. Most cores exhibit high values of $^{234}Th_{exc}$ (t1/2 = 24 days) at the top of the cores. These activities testify that the mud-rich layer is a very recent deposit. The settlement of this very thin (a few mm) surficial layer could be the result of continental-born material (river floods) where estuarine plumes reach the mid-shelf or of another (i.e. marine) source.

In a few cores (GAS_AA1, GAS_BB2 and TRO2_AA1) excess ^{234}Th activity was very low or not even present. In these cases, it should be considered that the surficial mud-rich layer was deposited several months ago before sampling. Several mechanisms could explain the presence of the old layer: (1) a sorting of the sediment during the coring (i.e. winnowing of mixed sediment and delayed deposition of fine particles related to the coarser ones), (2) a selective biological reworking, or (3) re-suspension and re-deposition events of old material (storm event or trawling effect).

As a whole, it appears that the northern part of LGV (station G) is a preferential depositional area for the fine particles. It corresponds to a hole where the muddy sediments are thicker (ca. 3m) in the whole northern shelf of the Bay of Biscay (Vanney, 1977; Bourillet et al., 2005). This depocentre is the result of several interfering causes: (1) the hydrological pattern (i.e. relatively low current velocities, protection against storms), (2) the closeness of river-borne suspended matter supplies (the Loire and the Vilaine and the small rivers of south Brittany), and (3) an assumed less heavy impact of fishing activity. In the central zone (stations A, B, C and D), due to weak currents and spreading of the estuarine plumes, a surficial mud-rich deposit can occur in summer (i.e. during fairweather conditions), by the settling of suspended matter in the water depths below the mean wave activity.

5.2.3. Seasonal trends in the surficial sediments

In the northern part of LGV (as studied in 2002), there is a general tendency of a rise in the fine sedimentation and an increasing activity of radionuclides in the more surficial sediments with the sampling conditions (i.e. the season). More generally (e.g. Nittrouer et al., 1984-1985, Nittrouer and Wright, 1994), the distribution of the fine particles in the surficial sediments can be explained as the result of the balance and the combination of the dispersion of estuarine plumes over the shelf and of the circulation of water masses (i.e. density-driven currents and wind stress). In winter, fluvial discharges and continental outputs of suspended matter to the Bay of Biscay shelf are the more important. However, an oceanic thermo-haline wedge occurs on the shelf around 100 m depth; this wedge acts as a filter between estuarine waters and marine waters (Castaing et al., 1999). Then, turbid waters are restricted to the inner to mid-shelf. Estuarine waters originating in the Gironde and the Loire rivers spread out toward the north of the shelf, and then suspended matter is possibly deposited in LGV. It is even postulated that the location of this wide muddy area is linked to the long-term stable situation of the thermo-haline front that separates oceanic waters from the colder and less salty coastal waters (Castaing et al., 1999). As warming occurs in April, the thermocline and thermohaline can establish gradually, separating bottom oceanic waters from fresh surface waters. However in the same period, river flows and associated outputs of fine material decrease and surface estuarine waters have low turbidities. At the end of the spring, the estuarine plumes are still abundant in fine particles, but there is a change in direction towards the south or the open ocean (Lazure and Jegou, 1998). Then, storm events remain rare; this corresponds to the increasing area of LGV in summer, as noticed by several authors (e.g. Pinot, 1974).

The general increase of fine material in surface sediments from April to September corresponds to the transition from a high suspended matter fluvial supply but high-energy setting in winter to a low suspended matter supply but low fair-weather setting in summer. Radioisotope activities are indicative of the complexity of the fine sedimentation onto such a shelf. Several factors can interact: (1) a decreasing activity of short-lived natural radionuclides (^{234}Th), (2) a fresh supply of suspended matter and (3) a re-suspension and mixing with older material. Depending on the preponderance of one of these factors, excess ^{234}Th can increase (stations B, C, D) or decrease (station A) in the central zone, whereas it remained constant in the more northern station.

Relatively high excess ^{234}Th in April at the top of a box core (station A) can be the result of the winter sedimentation, while fine sediments sampled in summer (June and September) should be the result of successive supplies, after a few months. In the more nearshore station G, constant ^{234}Th activities with time reveal a progressive sedimentation and no re-suspension processes, whatever the season.

6. Conclusions

The present study on the surficial sediments of “La Grande Vasière” (LGV) extends recent findings to this wide muddy mid-shelf; the whole area has now been studied from the Glenan islands at the north to Rochebonne shoal at the south. It provided the first set of data on modern fine sedimentation on the sandy continental shelf of the Bay of Biscay.

The main results are:

(1) Grain-size and radionuclide analyses made it possible to improve our understanding of the mechanisms of deposition of fine sediments on the mid-shelf. Lithology and grain-size analyses confirmed that LGV corresponds to a wide muddy sand area in which fine sediment content does not exceed 30%. One exception is the most northern and southern areas, south of Brittany and the southwest Rochebonne shoal, respectively. As a consequence, the two extremities of LGV (Glenan Islands and Rochebonne holes) are the two depocenters of fine sedimentation.

(2) Except for these two stations where mud was rather homogeneous, the box cores displayed a fining upward sequence in the top 20-30 cm. This feature of LGV can be interpreted as the result of extreme storm events.

(3) X-Ray imagery and the results of the radionuclide activities demonstrated that the sediments are strongly mixed, with a surface mixed layer of 7 - 20 cm. Several factors interact in the mixing process including biological and fishing activities. Although typical of this shelf, no sedimentary features of strong storms (e.g. fine sand laminae) were recorded in the deposits, except from the upward fining up decimeter-scale sequence.

(4) Excess ^{210}Pb data enabled estimation of accumulation rates of about 2 mm yr^{-1} in several stations of LGV. This rate is a maximum value, but it is of the same magnitude as previous results concerning the muddy sediments from the southern area of this shelf.

(5) The frequent occurrence of a thin mud-rich layer at the top of the sediments at many stations provided evidence for the settling of present-day fine sediments. The short lived radionuclide ^{234}Th revealed a present-day accumulation of fine sediments, probably

linked to the supply of suspended matter from the river-borne surface plumes in the study area. However, this radionuclide displayed complex variations at the scale of a year: in the central zone, maximum excess ^{234}Th was recorded in spring (April), but several stations showed maximum values in September due to preferential sedimentation when the swell regime was weak.

LGV is thus a wide and monotonous sand blanket that is subjet to modern supplies of river-borne fine material during their transfer towards the continental margin. It is not a mud field, but a patchwork of heterolithic and palimpsest sandy bottom where, depending on the hydrological setting on the shelf, mud settles preferentially during the summer. As a whole, the pattern of LGV is very complex, as it is also the location of intensive removal and mixing that can be attributed to storm swells, benthic biological and fishing activities.

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Figure captions :

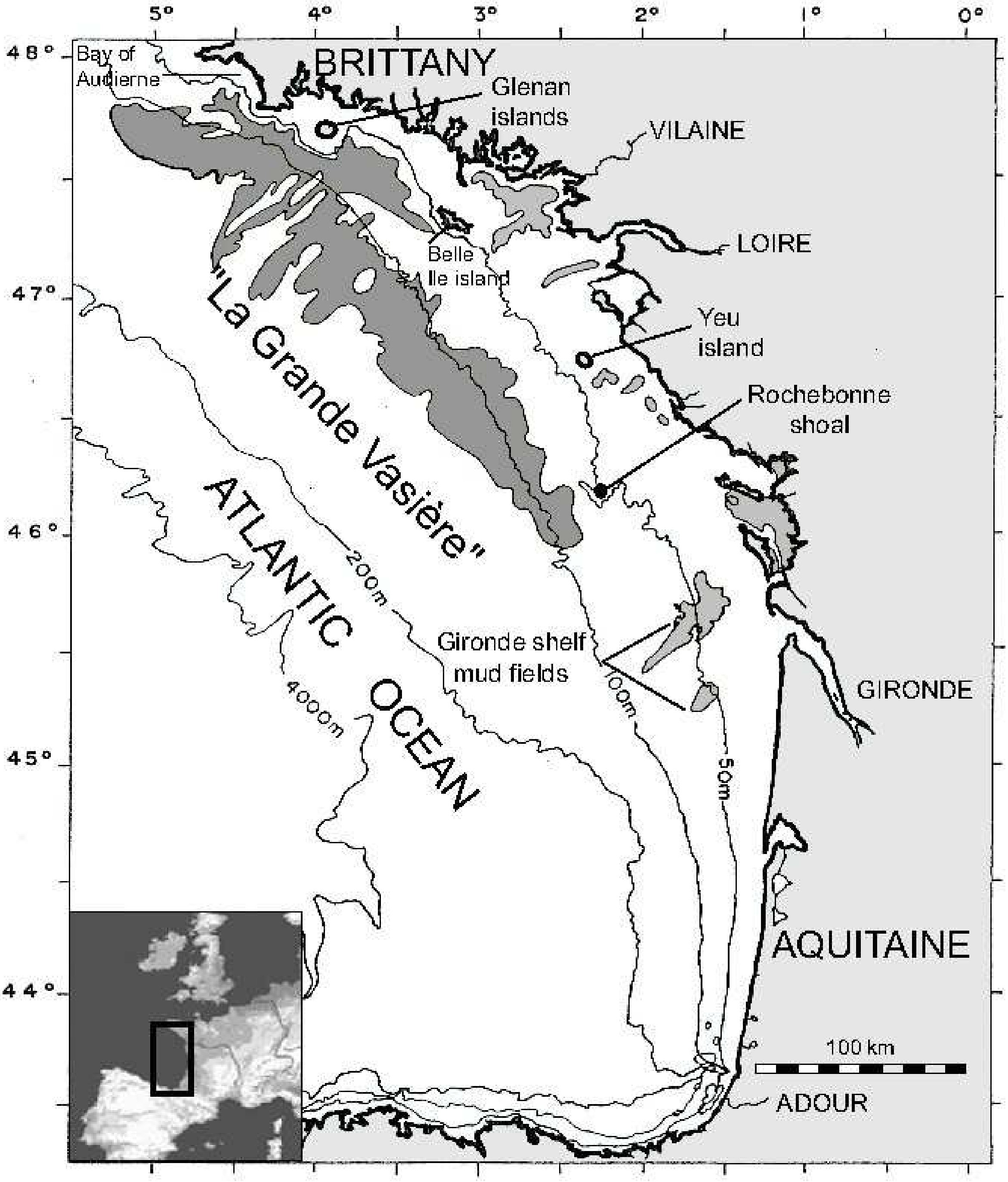


Figure 1: Map of the continental shelf of the Bay of Biscay (France) including mud shelf deposits, coastal bays and open shelf mud fields. La Grande Vasière (LGV) is in dark gray. Other fine-sediment areas are in light grey, including the Gironde shelf mud fields and the muddy coastal bays.

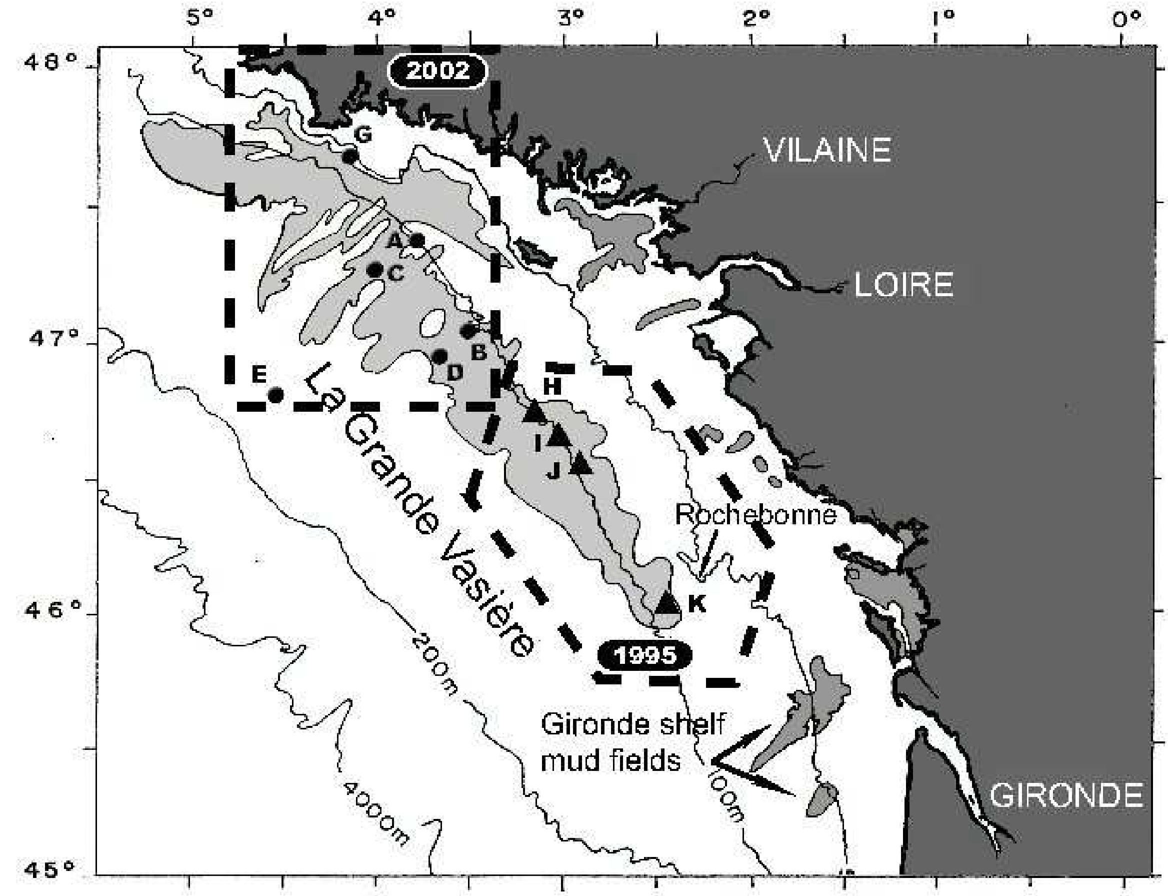
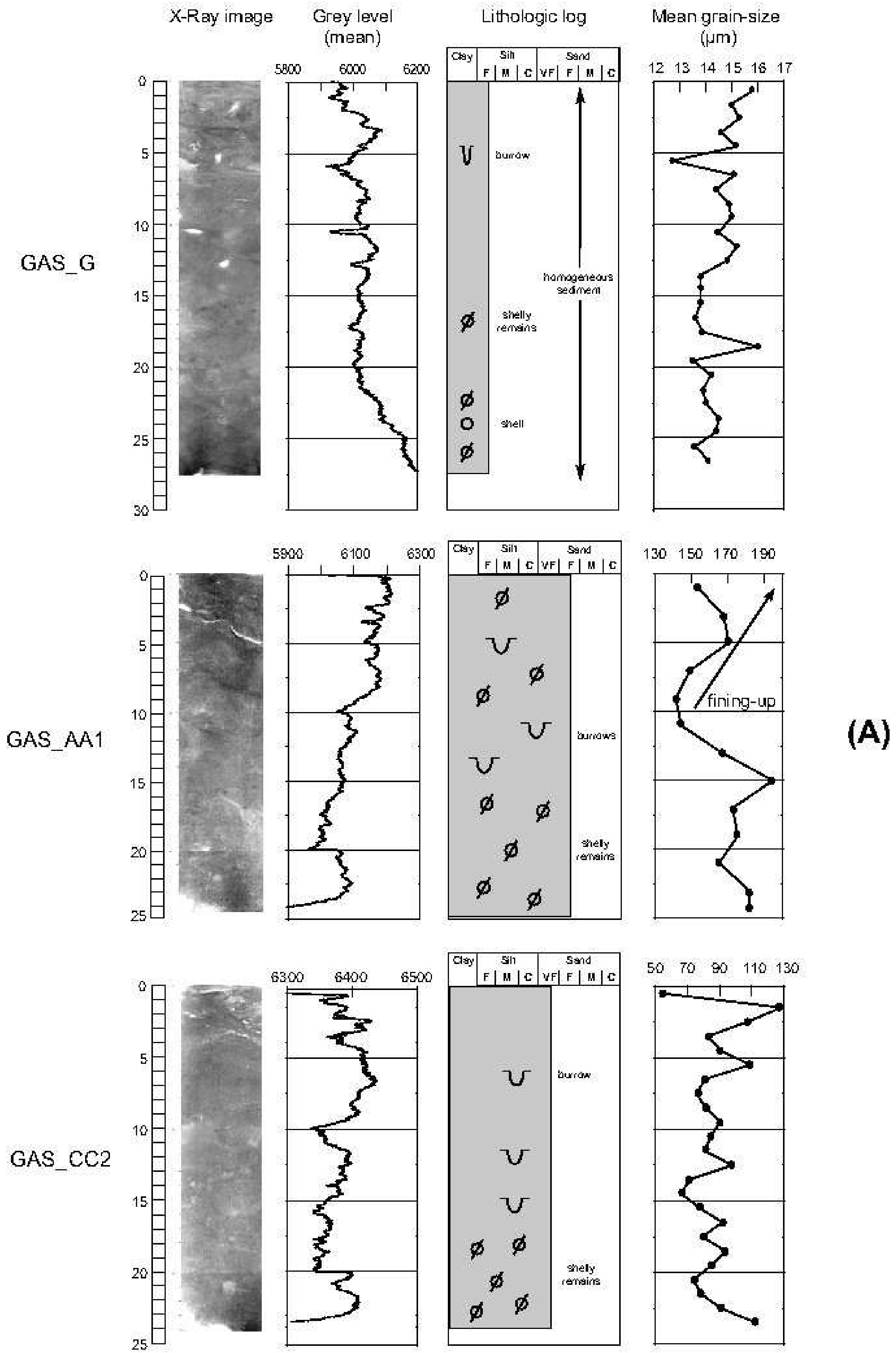


Figure 2: Locations of the box cores sampling stations in the study area of La Grande Vasière (LGV). The location of the surficial sediments during the 2002 cruises in the northern area (GASPROD, TROPHAL 1, TROPHAL 2) are shown as dots (A, B, C, D, E, G). The location of the box cores sampled in 1995 in the southern part of LGV are shown by triangles (stations H, I, J, K).


X-Ray image
Grey level (mean)
Lithologic log
Mean grain-size (µm)
GAS_G
burrow
homogeneous sediment
shelly remains
shell
GAS_AA1
fining-up
burrows
shelly remains
GAS_CC2
burrow
shelly remains
Clay
Silt
Sand
(A)

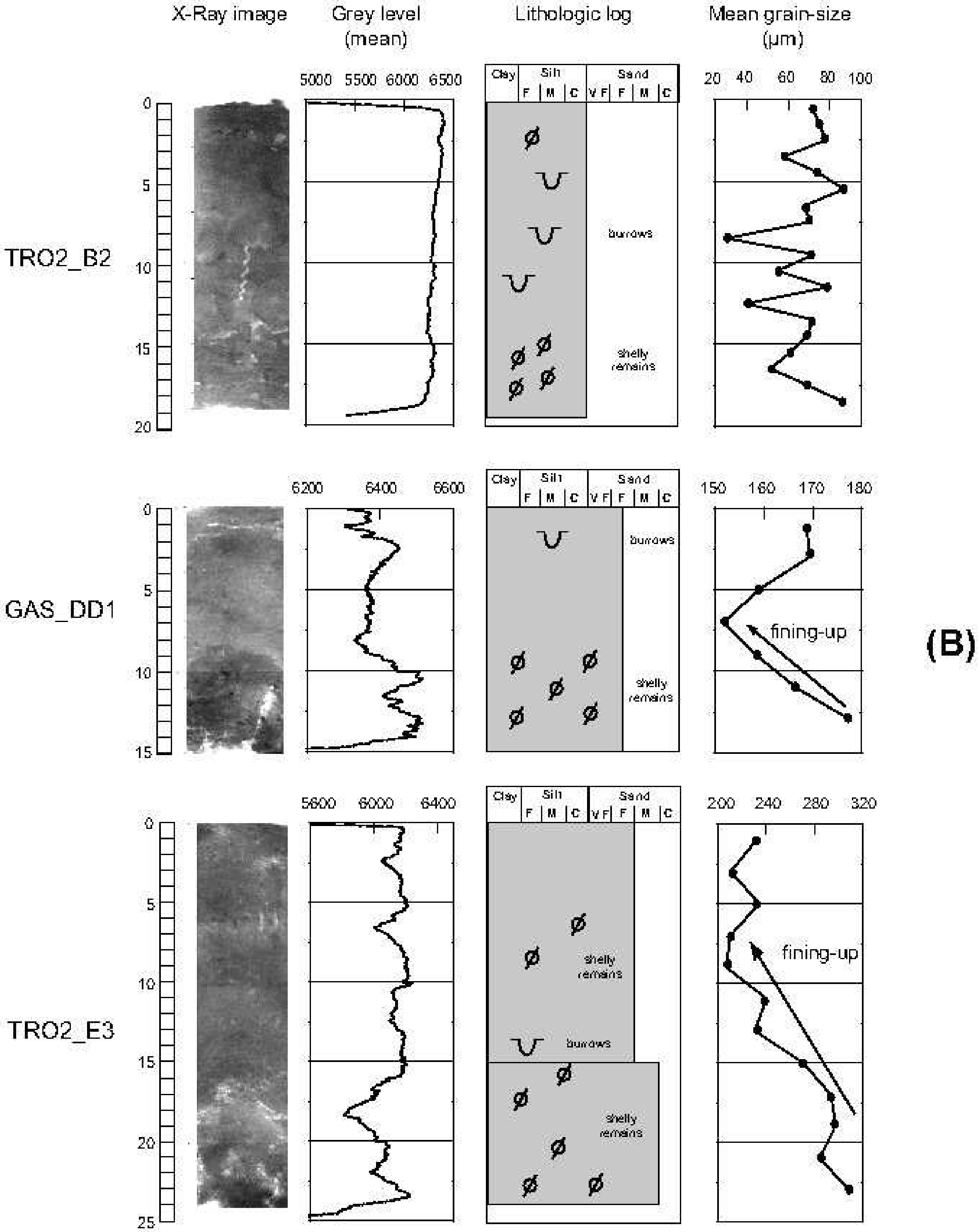


Figure 3: Radiographs (positives, mud in light grey and coarse sands in dark grey) and associated grey levels, lithologic logs, mean grain-size for six box cores.

(A): GAS_G (station G, April 2002, latitude 47° 36.010' N, longitude 4° 10.000 W, depth 80 m), GAS_AA1 (station A, April 2002, latitude 47° 13.800'N, longitude 3° 40.200 W, depth 100 m) and GAS_CC2 (station C, April 2002, latitude 47° 9.000'N, longitude 3° 55.800 W, depth 110 m);

(B): TRO2_B2 (station B, September 2002, latitude 46° 5 7.030’N, longitude 3° 24.970 W, depth 102 m), GAS_DD1 (station D, April 2002, latitude 46° 52.077’N, longitude 3° 42.024 W, depth 80 m), and TRO2_E3 (station E, September 2002, latitude 46° 54.907’N, longitude 4° 29.405 W, depth 138 m).

Note that the grey-scale intensity of the X-ray image is a function of the sediment density (slice samples are 10 cm long, Scopix method).

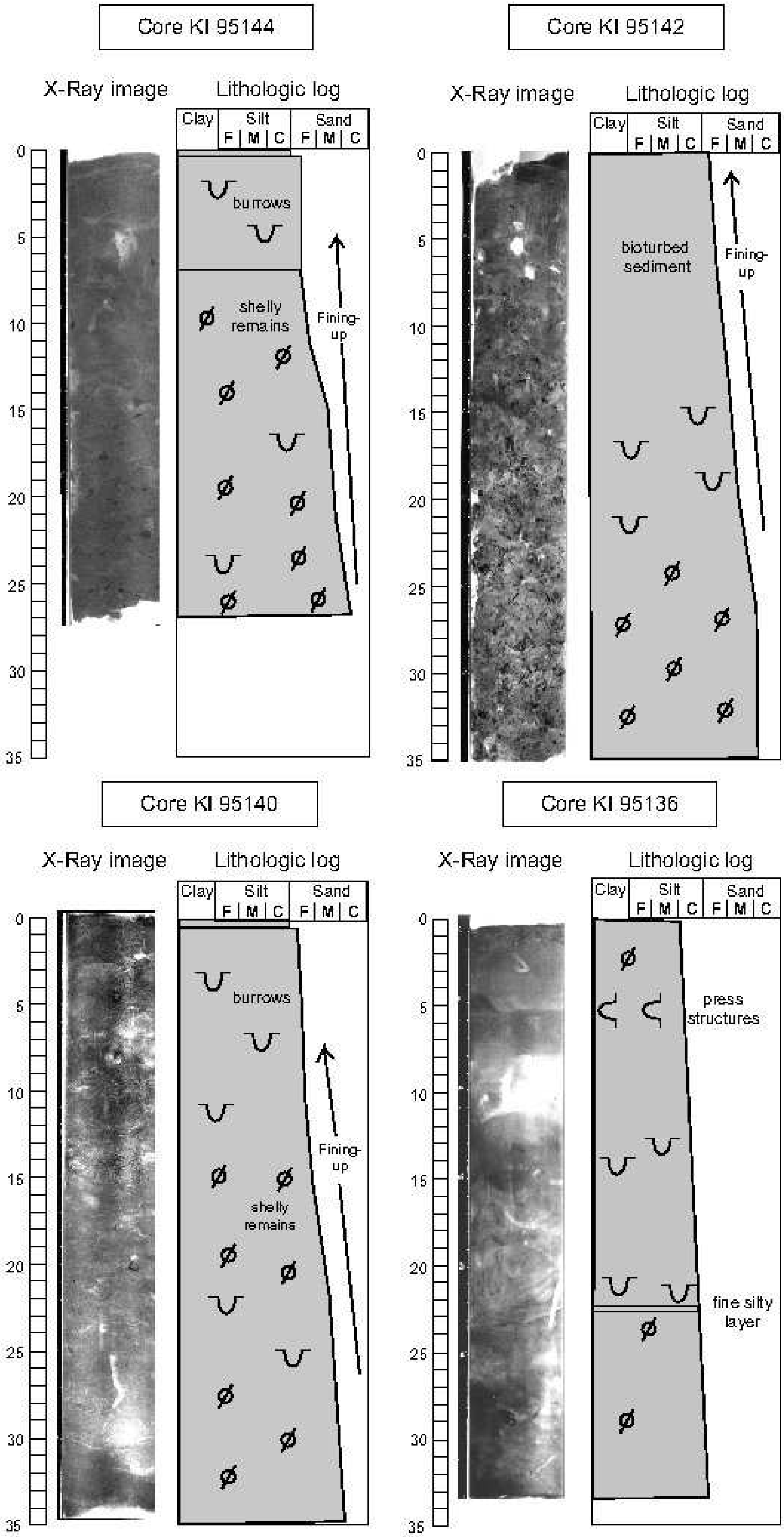


Figure 4: Radiographs (positives, mud in light grey and coarse sands in dark grey) and lithologic logs of four box cores sampled in June 1995 in the southern area of La Grande Vasière. Core KI_95144 (latitude 46° 43' 968 , longitude 03° 08' 178, water depth 100 m, station H); core KI_95142 (latitude 46° 35' 978, longitude 02° 58' 567,

water depth 100 m, station I); core KI_95140 (latitude 46° 28’ 003, longitude 02° 52’ 754, water depth 99 m, station J); core KI_95136 (latitude 46° 09’ 996, longitude: 02° 37’ 443, water depth 95 m, station K). Note that the sediments are strongly bioturbated, but they display an upward fining up tendency (dark arrow) from coarse/medium sands to fine sands and then a surficial fine-sediment.

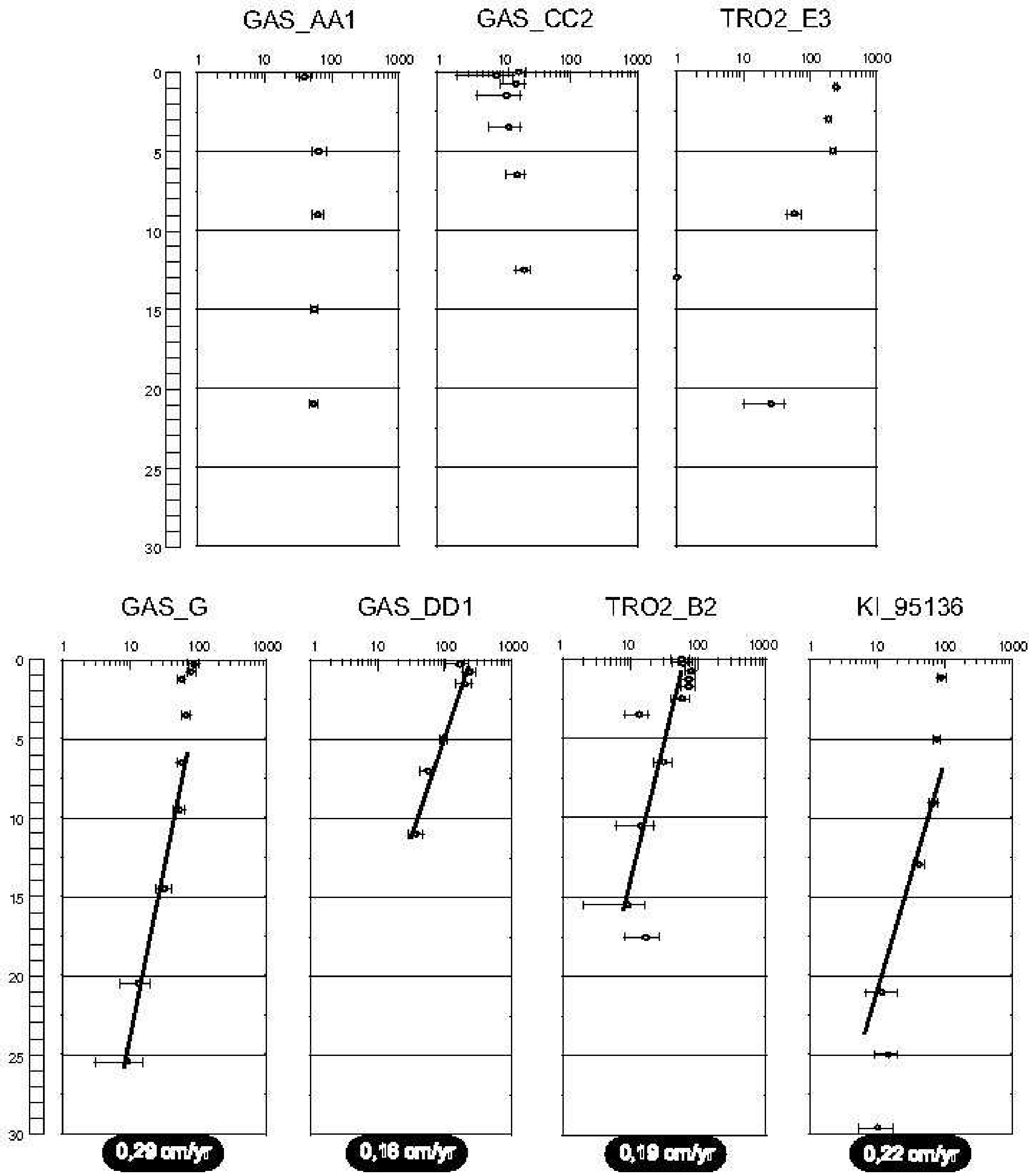


Figure 5: Profiles of excess ^{210}Pb activity in seven box cores of the study area of La Grande Vasière. GAS_AA1 (station A, central zone); GAS_CC2 (station C, central zone); TRO2_E3 (station E, central zone); GAS_G (station G, northern area); GAS_DD1 (station D, central zone); TRO2_B2 (station B, central zone); KI_95136 (station K, southern area, Lesueur et al., 2001).

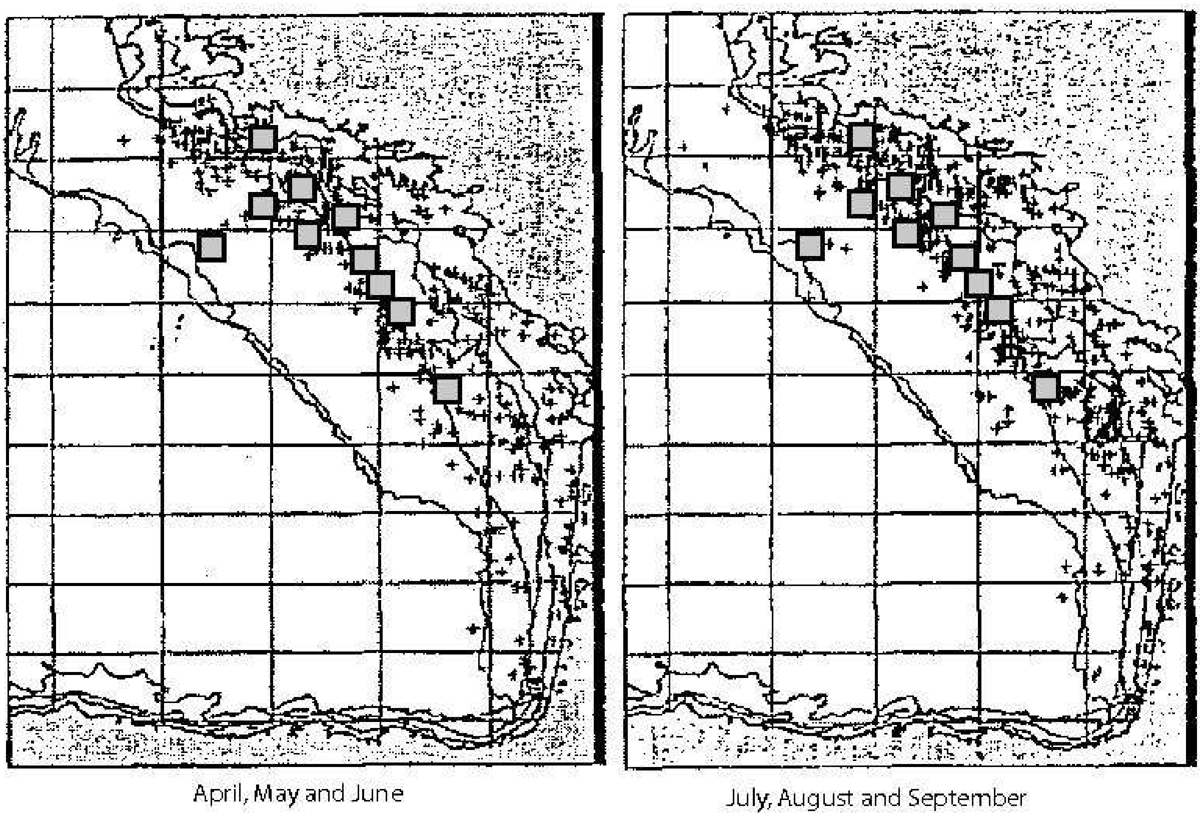


Figure 6: Locations of bottom trawlers on the shelf of the Bay of Biscay in two quarters of the year (black crosses, after Léauté, 1998) and locations of box cores in 1995 and 2002 (grey squares, this study). Note the superposition of the box cores with the intensively fished areas.

Table captions:

Cores	Depth (m)	Mean (µm)	Median (µm)	Classes of grain-size (µm)					Mode (µm)			
				> 500 (%)	250-500 (%)	125-250 (%)	63-125 (%)	<63 (%)	First	%	Second	%
April 2002												
GAS_AA1	100	156.2	184.6	5.1	21.3	58.4	5.8	9.2	125-250	58.4	250-500	21.3
GAS_BB2	102	138.6	187.2	12.2	24.7	36.4	10.4	16.3	125-250	36.4	250-500	24.7
GAS_CC2	110	90.2	178.2	0.8	28.4	33.8	7.5	29.3	125-250	33.8	<63	29.3
GAS_DD1	114	161.4	223.8	2.9	32.3	49.7	3.7	11.4	125-250	49.7	250-500	32.3
GAS_G	80	14.8	10.6	0	0.5	2.6	8.1	88.7	<63	88.7	63-125	8.1
September 2002												
TRO2_AA1	96.5	122.3	228.4	6.9	37.4	27.3	4.5	23.8	250-500	37.4	125-250	27.3
TRO2_B2	102	68.4	134.6	0.2	17.1	36.9	10.1	35.6	125-250	36.9	< 63	35.6
TRO2_CC2	109.5	90.8	183.8	0.5	28.8	34.4	7.2	28.9	125-250	34.4	< 63	28.9
TRO2_D2	120	192.7	279.7	12.5	44.3	25.8	6	11.3	250-500	44.3	125-250	25.8
TRO2_E3	138	218.4	247.3	12.3	36.1	40.6	3.6	7.3	125-250	40.6	250-500	36.1
TRO2_G	90	14.3	10.4	0	0.1	1.5	7	91.3	< 63	91.3	-	-

Table 1: Grain-size distributions of the surficial sediments in 11 box cores taken in the northern area of La Grande Vasière (mean values of the ten top cm).

STATIONS	Purcentage in fine fraction (< 63µm)		$^{210}Pb_{exc}$		$^{234}Th_{exc}$	
	April 2002	September 2002	April 2002	September 2002	April 2002	September 2002
A	11	24	40	200	149	30
B	17	36	13	59	29	66
C	30	29	40	170	105	543
D	12	12	19	68	93	168
E	-	6	-	250	-	46
G	88	92	101	114	225	211

Table 2: Fine-sediment content (< 63 □m), $^{210}Pb_{exc}$ activities (in Bq kg^{-1}) and $^{234}Th_{exc}$ activities (in Bq kg^{-1}) in the more surficial sediments (the top cm) in the study area of La Grande Vasière during the sampling periods in April and September 2002. (- indicates the absence of a sample).

Date	Stations	Cores	Depth in the core (cm)	$^{234}Th_{exc}$ (mBq)	$^{234}Th_{exc}$ inventories (mBq)
April 2002	C	GAS_CC2	0.3	17.85	61.01
			0.8	17.02	
			1.3	15.44	
			1.8	10.70	
	D	GAS_DD1	0.3	-	111.18
			0.8	62.05	
			1.3	29.76	
			1.8	19.36	
September 2002	B	TRO2_B2	0.3	8.40	31.55
			0.8	10.99	
			1.3	5.08	
			1.8	7.08	
			2.3	0.00	
	C	TRO2_CC2	0.3	65.78	102.10
			0.8	14.26	
			1.3	11.71	
			1.8	10.35	
			2.3	0.00	
	E	TRO2_E3	0.3	20.89	59.90
			0.8	27.86	
			1.3	7.83	
			2.3	3.31	
	G	TRO2_G	0.8	78.90	151.58
			1.3	41.91	
			1.8	16.51	
			2.3	14.25	

Table 3: Excess ^{234} Th inventories in the top 3 cm of six cores (in mBq) of the study area of La Grande Vasière during the sampling periods in April and September 2002.