Determination of sediment accumulation and mixing rates in the Gulf of Lions, Mediterranean Sea

Gulf of Lions
^{210}Pb
^{137}Cs
Biological mixing
Accumulation rate

Golfe du Lion
^{210}Pb
^{137}Cs
Bioturbation
Taux de sédimentation

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ABSTRACT

Sediment mixing and accumulation rates in the Gulf of Lions were determined, applying the ^{210}Pb and ^{137}Cs dating methods to a total of 20 boxcores taken in 1987, 1988 and 1989.
The distribution of excess ^{210}Pb profiles indicated the presence of surface mixed layers in the nearshore sediment cores which ranged from 3 to 15 cm. The apparent ^{210}Pb accumulation rates varied from 0.02 to 0.63 cm.yr^{-1} in this study area. Rates were highest near the river mouth of the Rhône and decreased with increasing water depth and increasing distance from the river mouth.
Observed depths of ^{137}Cs penetration within the sediments were compared with depths predicted from the surface mixed layer thickness and the ^{210}Pb accumulation rate. These showed a general agreement but one station suggests that there are some effects of relatively deep mixing below the intensely mixed surface layer. However, the agreement of ^{210}Pb and ^{137}Cs data of most stations indicates a general absence of deep mixing in the Gulf of Lions. Therefore, the apparent accumulation rates calculated from the ^{210}Pb profiles (below the surface mixed layer) generally reflect the true sedimentation rates.
From the sedimentation distribution, the annual amount of sediment deposited in this study area was estimated to be 10.1 x 10^9 kg. yr^{-1}, of which 30 % is biogenic and at least 20 % is contributed by atmospheric input. It is concluded that most of the sediment supplied by the Rhône river was deposited near the river mouth, and the remainder on the continental shelf and the upper slope, only a small amount being transported to the deep-sea basin.

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RÉSUMÉ

Taux de sédimentation et de mélange des sédiments du golfe du Lion, Mer Méditerranée

Les taux de sédimentation et l'intensité de bioturbation des sédiments du golfe du Lion ont été déterminés à partir de la distribution du ^{210}Pb et du ^{137}Cs dans vingt prélèvements de sédiment effectués en 1987, 1988 et 1989.
La distribution verticale du ^{210}Pb en excès indique la présence de couches de mélange superficielles (SML), dont l'épaisseur varie de 3 à 15 cm, dans les sédi-

ments côtiers. Les taux de sédimentation sont maximaux (0,63 cm.an^{-1}) près de l'embouchure du Rhône et diminuent, avec l'augmentation de la profondeur et de la distance à l'embouchure jusqu'à des valeurs de 0,02 cm.an^{-1}.
La pénétration de ^{137}Cs observée dans les sédiments a été comparée à l'épaisseur présumée de la couche de mélange superficielle et au taux de sédimentation mesuré à partir du ^{210}Pb. A l'exception d'un prélèvement, on obtient une bonne corrélation entre les deux types de données, ce qui laisse supposer que les sédiments stiués sous la SML ne sont pas affectés par la bioturbation ou par d'autres processus de mélange. Les taux de sédimentation apparents calculés à partir des profils du ^{210}Pb en excès sous la SML sont donc les vrais taux de sédimentation.
La quantité totale de sédiment accumulée annuellement dans la zone étudiée a été estimée à 10,1 x 10^9 kg.an^{-1}, dans laquelle 30 % environ sont d'origine biogénique, et au moins 20 % d'origine atmosphérique. La plus grande partie est déposée près de l'embouchure du Rhône, presque tout le reste sur le shelf et la partie supérieure de la pente continentale, et seulement une petite fraction dans le glacis et le bassin.

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INTRODUCTION

The Gulf of Lions is an important feature of the Mediterranean coastline of France (Fig. 1). The deposit of sediment in this area is governed not only by the intricate topography of the sea bed but also by the terrigenous input and water circulation. The steep continental slope is indented by a large number of submarine canyons which constitute about 50 % of the slope surface. This margin is characterized by relatively low annual sediment inputs, irregularly discharged over the years due to the Mediterranean climatic conditions (Courp and Monaco, 1990). The Rhone river is the dominant (80 %) source of sediment for the continental shelf of the Gulf of Lions. Pauc (1970), Blanc (1977) and Leveau and Coste (1987) have suggested that the annual discharge by the Rhone river is 3-5 x 10^9 kg.yr^{-1}. Water circulation is mainly controlled by the Liguro-Provencal current (Monaco *et al.*, 1987; Millot, 1987), a NE-SW flow, on which the outflow plume of the Rhone river is superposed. Besides a direct feeding of material from the continent by the Rhone river and other less important coastal rivers, atmospheric input from the Sahara desert dust and biogenic (carbonate, organirc matter, opal, *etc.*) production that are produced in the surface water also play important roles in the depositional system of the Gulf of lions. Applying ^{210}Pb and ^{137}Cs dating method measurements to a total of 20 boxcores, this paper discusses quantitative analyses of accumulation, mixing and distribution of bottom sediments in the Gulf of Lions. Preliminary results of this work were published in the proceedings of the EROS-2000 meeting in Paris in 1989 (Water Pollution Research Report 13, Zuo *et al.*, 1989 *b*).

SAMPLING AND MATERIAL

In 1987, 12 boxcores were collected by the Nehterlands research vessel *Tyro* in the area of the Gulf of Lions. A year later, seven other boxcores were taken during a cruise with the English research vessel *Discovery.* An additional eight boxcores were obtained in 1989 during a cruise of the Italian research vessel *Bannock.* Out of the twelve cores collected in 1987, four were not used for dating because two were very sandy and two others were duplicates. Also the core taken at station 8908 in 1989 was not analysed because its location was close to that of the core taken at station 8917, but all cores collected in 1988 were used for geochronological dating. Not taken into account is core RT2 from the river mouth area, because it did not penetrate the top mixing layer. Figure 1 shows the location of the boxcores which are the subject of this paper.

The boxcores were subsampled with PVC pipe (6 cm Ø), and were stored upright to avoid mixing of the soft top layer during transportation. The sediment cores were split, described and an X-ray radiograph was made for each core. The subsampling was made at 1-3 cm intervals for ^{210}Pb and ^{137}Cs dating. The determination of water content in the sediment was done to calculate sediment porosities (Ø) according to Anderson *et al.* (1987):

$$Ø = \frac{\%W}{\%W + (1 - \%W) / p_s} \qquad (1)$$

where %W is the measured water percentage by weight and p_s is the dry density of the sediments, which was assumed to be 1.60 g.cm^{-3} for this study area. The carbonate content is 25-30 % in the nearshore coastal sediments and 40-50 % in the offshore sediments (Nolting, 1989).
The sediments cores, according to both X-ray radiographs and observation, showed distinct differences between the nearshore cores (< 1000 m) and the offshore cores (Fig. 1). Clay or silty clay were dominant in the former, together with a disturbed top layer. Cores showed numerous small burrows and tubes ranging from 1-5 mm in diameter. Though in cores ME1 and 8725 a mottled structure with many shell and shell fragments was present, X-ray radiographs showed little burrowing below the surface mixed layer (SML). The foraminifera and many other

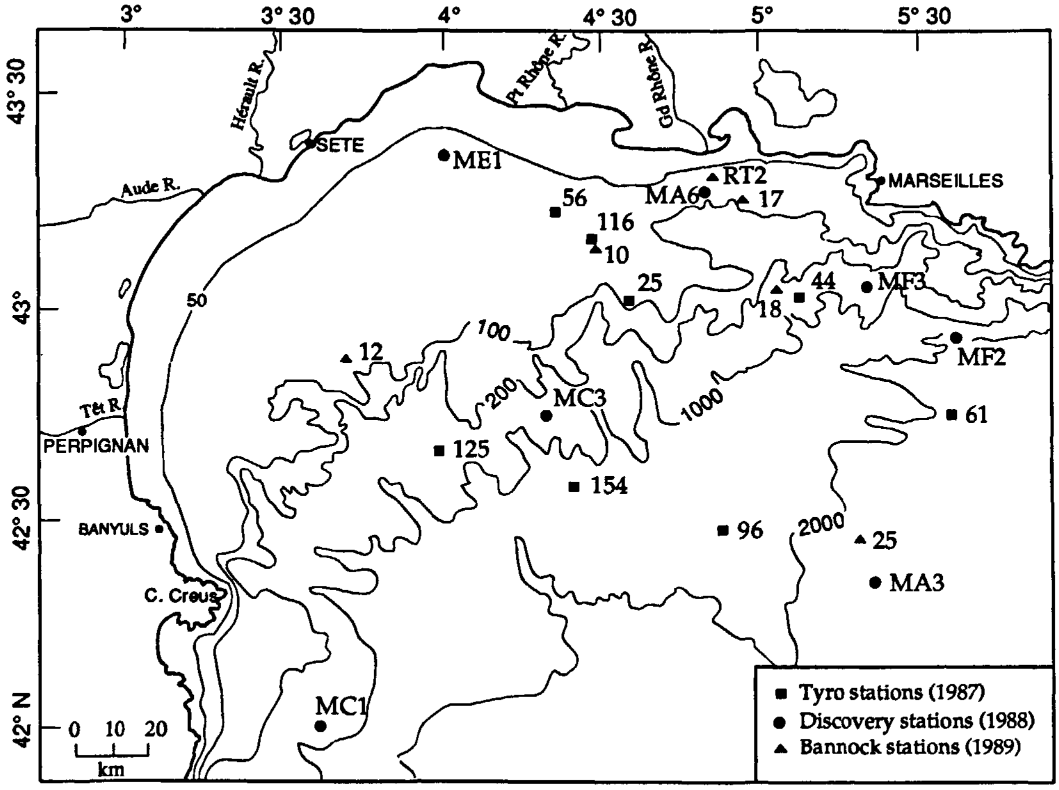

Figure 1

General map of Gulf of Lions, Mediterranean Sea, showing the location of boxcores collected in 1987, 1988 and 1989.

elements of the indigeous meiofaunal community are generally confined to the uppermost centimetre of the sediment due to their feeding habits (Smith and Schafer, 1984), which indicates that the bioturbation processes were mainly restricted in the surface zone, ranging in this area from a few centimetres to about 15 cm. In cores taken from areas deeper than 1000 m, grey or brown grey clay with uniform or weakly layered structure were observed. The X-ray radiographs exhibited faint beddings in the sediment, which suggests that the deep water area might be an inhospitable environment for burrowing macrofauna.

DATING METHODS AND MIXING

The use of the natural radionuclide ^{210}Pb to determine marine and freshwater sedimentation is now a well established technique (El-Daoushy, 1978; Chanton *et al.*, 1983; Binford and Brenner, 1986; Berger *et al.*, 1987; Eisma *et al.*, 1989). Its half-life of 22.3 years makes ^{210}Pb a powerful tool in relating sedimentation to oceanic processes which have occurred during the past 100 years or so. ^{210}Pb is brought into the sediment both by *in situ* production through radioactive decay of ^{226}Ra (supported ^{210}Pb) as well as by deposition of the decay product of ^{222}Rn (excess ^{210}Pb) which is produced in the atmosphere and in the water column. Being a beta emitting nuclide, ^{210}Pb cannot directly be measured by alpha spectrometry. Therefore, the ^{210}Pb activity is determined indirectly by measuring its alpha emitting granddaughter ^{210}Po (half-life 138 days). Secular equilibrium between these two nuclides is reached in approximately two years so that in older natural systems the ^{210}Po activity equals the ^{210}Pb activity, provided that the sediments acts as a closed system with respect to lead and polonium (Van der Wijk, 1987).

If we assume that the deposition of ^{210}Pb is at steady state, then the ^{210}Pb profile can be used to calculate the accumulation rate (S) using the following relationship (Robbins and Edgington, 1975; Goldberg *et al.*, 1977; Anderson *et al.*, 1987):

$$S = \frac{}{\ln (A_0/A_z)} \qquad (2)$$

where:

A_0 = excess ^{210}Pb activity at the sediment surface (dpm.g^{-1});

A_z = excess ^{210}Pb activity at depth z (dpm.g^{-1}) below level of A_0;

λ = decay constant of ^{210}Pb (= 0.03114 yr^{-1}) and

Z = depth.

Seldom is sediment accumulation a simple burial of particles. In marine environments, sedimentation can undergo significant change on time scales of 100 years. Typical accumulation rates on continental margins are millimetres to centimentres per year (Nittrouer *et al.*, 1983/1984), therefore the last 100 years of accumulation are represented by the upper metre or so of the seabed. This is also the region reworked by mixing processes, especially by benthic organisms, which complicate the mechanism of sediment accumulation and the interpretation of ^{210}Pb profiles. The biological mixing process modelled as a diffusion process (Guinasso and Schink, 1975; Nittrouer *et al.*, 1983/1984; DeMaster *et al.*, 1985) is given by the advec-

$$D_B \frac{\partial^2 A}{\partial Z^2} - S \frac{\partial A}{\partial Z} - \lambda A = 0 \qquad (3)$$

tion-diffusion equation:
where D_B is the particle mixing coefficient ($cm^2.yr^{-1}$); the other terms are as defined above. The solution to this equa-

$$S = \frac{}{\ln (A_0/A_z)} - \frac{D_B}{Z} [(\ln.A_0/A_z)] \qquad (4)$$

tion can be rearranged for calculation of accumulation rate If mixing is negligible ($D_B = 0$), equation 4 simplifies to equation 2. However, if mixing is present, equation 4 demonstrates that consideration of only accumulation and radioactive decay provides an apparent accumulation rate which overestimates the true accumulation rate. In equation 4, there are two unknown parameters (D_B and S). To solve this, ^{137}Cs measurement was used in conjunction with ^{210}Pb dating method (Robbins and Edgington, 1975). In some cores (MA3, 8925, 8796 and 8761) fine undisturbed bedding with at most a few small burrows indicated that D_B is 0 or very nearly 0.

The particle-reactive isotope ^{137}Cs (half-life 30 years) is a fission product initially introduced into the environment as a result of nuclear weapons testing. Significant amounts of ^{137}Cs deposition began to occur in about 1953 and the maximum ^{137}Cs concentration in the sediment corresponds to the 1963 maximum in atmospheric ^{137}Cs fall out. This approach presumes that: 1) the time between atmospheric production and ^{137}Cs arrival at the seabed is short; 2) there is no intensely mixed surface layer. Under these conditions, the depth of ^{137}Cs penetration into the seabed can be measured and related to the mixing and accumulation rates by incorporating the dispersion-advection equation (Guinasso and Schink, 1975):

$$H = (2D_B t)^{1/2} + St \qquad (5)$$

where H is the depth of penetration (cm) for particles with ^{137}Cs activity, and t is the elapsed time (yr) since ^{137}Cs activity reached the seabed. ^{134}Cs is also a man-made radionuclide with a much shorter half-life of two years. In our study area it is strongly related to the river input because of the release from the power plants located upstream on the Rhône river. However, it is possible to use Cs isotopes as the best potential tool to check ^{210}Pb accumulation rates (Robbins *et al.*, 1978; Von Gunten *et al.*, 1987; Wan *et al.*, 1987).

For ^{210}Pb dating, samples of 0.5 g (dry weight) were spiked with a known amount of ^{208}Po as a yield tracer and leached with HF, $HClO_4$, HNO_3 and HCl solutions. The Po-isotopes were plated on silver discs at 85°C after reduction of Fe^{3+} with ascorbic acid and analysed using a-spectroscopy. The supported ^{210}Pb activity was obtained by measuring the ^{226}Ra concentration and assuming secular equilibrium with ^{210}Pb, or by measuring ^{210}Pb in sediments old enough to accept that all the unsupported ^{210}Pb has decayed and assuming that supported ^{210}Pb is constant.

For cesium dating, about 20 g of dried sediment was taken for each sample at intervals of 1-3 cm. The concentration of cesium was measured nondestructively in a high-resolution Germanium detector for about 24 hours to obtain enough counts. Activity of ^{137}Cs was calculated by integrating the counts under the peak at 662 KeV and activity ^{134}Cs was determined by integrating counts under the peaks at 604 and 795 KeV.

RESULTS AND DISCUSSION

Lead- 210 distribution and apparent accumulation rate

Table 1 lists surface mixed layer depth (L), the apparent accumulation rate (S) and the sediment flux (R) derived from the excess ^{210}Pb activity-depth profiles in twenty cores.

Table 1

Sedimentation rates (S), fluxes (R), surface mixed layer depth (L, from ^{210}PB profiles) and water content (W, in upper 20cm) in 20 sediment cores.

Station	Mixing depth on X-radio-graph (cm)	Surface mixed layer L (cm)	Water depth (m)	Accumulation S ($cm.yr^{-1}$)	Accumulation R ($g.cm^{-2} yr^{-1}$)	Water content W (%)
* 1987						
8725	n.b.	6	100	0.15	0.12	39
8744	n.b.	2	420	0.13	0.11	35
8756	1	3	68	0.14	0.10	44
8761	≈0		2250	0.04	0.02	49
8796	≈0		1701	0.05	0.04	35
87116	n.b.		69	0.15	0.12	39
87125	n.b.		728	0.11	0.07	47
87154	n.b.		1270	0.11	0.08	41
*1988						
MA3	≈0		2230	0.02	0.02	36
MA6	n.b.	15	73	0.63	0.47	41
MC1	6		780	0.05	0.04	37
ME1	n.b.	8	49	0.18	0.17	30
MF2	n.b.	4	1100	0.08	0.05	47
MF3	n.b.	6	560	0.09	0.06	48
MC3	n.b.	5	260	0.17	0.13	40
*1989						
8910	n.b.	8	79	0.12**	0.09	40
8912	n.b.	3	98	0.15	0.14	30
8917	n.b.	8	90	0.20	0.16	39
8918	n.b.		390	0.12	0.09	42
8925	≈0		2160	0.03	0.03	35

n.b. = no bedding.
* the year in wich the boxcores were taken.
** calculated from ^{137}Cs profile (^{210}Pb not measured).

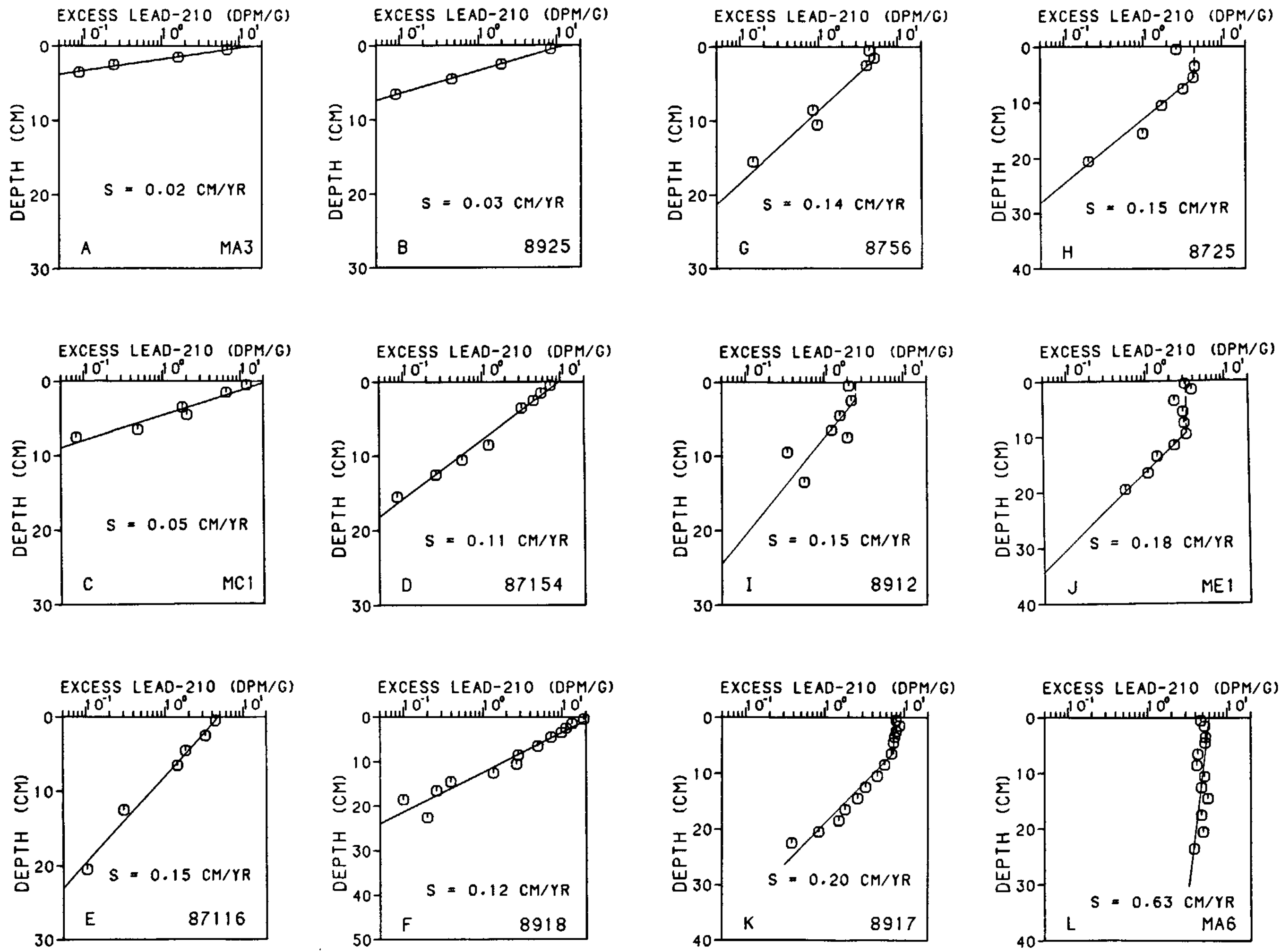

Figure 2

Semi-logarithmic profiles of excess ^{210}Pb activity against sediment depth

The sediment flux (R) was calculated according to the following equation

$$R = S\,(1 - \emptyset)\, p_s \qquad (6)$$

Near to the sediment-water interface, the ^{210}Pb activities ranged from 2.08 to 18.92 dpm.g^{-1}, which is higher than that in the sediments of the North Sea (0.7 to 1.2 dpm.g^{-1}; Zuo *et al.*, 1989 *a*). The values of ^{210}Pb background varied from 0.54 to 1.44 dpm.g^{-1}.

Two types of excess ^{210}Pb distribution were observed (Fig. 2):

1) the excess ^{210}Pb activities decrease exponentially downward the sediment-water interface with a constant gradient (MA3, 8925, 8761, 87154, 87116, 8918, MC1 and 87125; Fig. 2: A, B, C, D, E, F). In cores MA3, 8925, 8761 and 8796 this corresponds with the evidence from X- ray radiographs which show fine layerings in the top layers. MC1 in top layer of 6 cm shows some signs of bioturbation but is not very clear. All other cores of this group have no bedding and show signs of burrowing. Therefore, mixing is negligible in four cores and the ^{210}Pb apparent accumulation rates in these cores are representatives of the true accumulation rate. The cores belonging to this type were collected from the offshore area with relatively deep water (100- 2250 m);

2) Most of the cores in this type had uniform ^{210}Pb activities in the upper few centimetres, below which the excess ^{210}Pb activities decreased exponentially with depth (cores 8756, 8725, 8912, ME1, 8917, MA6, MF2, 8744, 8756 and MC3; Fig. 2: G, H, I, J, K, L). The surface mixed layer ranged from 3 to 15 cm. X-radiographic evidence of burrowing intersecting the top 15 cm interval indicates that the ^{210}Pb subsurface maximum was caused by rapid mixing of surface sediments possibly due to biological processes. The accumulation rates from those cores calculated below the mixed surface zone are maximum accumulatiuon rates because the effects of deep mixing below the surface mixed layer are not known.

The apparent sediment rates of twenty cores were ranged from 0.02 to 0.63 cm.yr^{-1} or 0.02 to 0.47 g.cm^{-2}.yr^{-1}. The highest rate (0.63 cm.yr^{-1}) was found at over 73 m depth, just off the Rhône river mouth (station MA6), while the lowest (0.02 cm.yr^{-1}) was found about 2000 m water depth (station MA3), far from the continental shelf and upper slope, which indicates a significant decrease of deposition rate with increasing water depth.

Cesium-137 distribution and penetration

Table 2 shows the concentrations of cesium isotope in the sediment of nine cores obtained from gamma spectrum measurements. The activities of ^{137}Cs ranged from 5 to 309 Bq.kg^{-1}, while the activities of ^{134}Cs were from 0.5 to 16.5 Bq.kg^{-1}.

Table 2

Concentrations of cesium isotopes in sediment cores.

Station	^{137}Cs (Bq. kg^{-1})		^{134}Cs (Bq.kg^{-1})		$^{134}Cs/^{137}Cs$ (%)	
	Range	Average	Range	Average	Surface	Average
MA6	81.9-141	118.9	0.5-16.5	8.2	12.5	6.9
ME1	7.8-66.6	45	0.0	-	-	-
8725	5-126	52.6	0.0	-	-	-
8910	32.2-241	170.9	0.0	-	-	-
8918	94.7-207	123.3	0.0	-	-	-
8917	31.7-309	148.1	0.0	-	-	-
MA3		5.4 (0-1.5 cm)	0.0	-	-	-
8 925		84.4 (0-1.5 cm)	0.0	-	-	-
MC1		14.2 (0-2 cm)	0.0	-	-	-

Figure 3 shows the activity-depth profile of radiocesium in nine sediment cores. Significant amounts of ^{134}Cs were only found in station MA6 (Fig. 3 *A*) just off the river mouth, and were accompanied by relatively high concentrations of ^{137}Cs.

Nittrouer *et al.* (1983/1984) have concluded that in a two-layer model (*i.e.* negligible mixing below the surface layer), the observed ^{137}Cs penetration should be the sum of mixed layer thickness plus sediment accumulation since ^{137}Cs emplacement (about 1953 for this study area). It is important to recognize that mixing below the surface layer will cause deeper penetration of particles (and ^{137}Cs) than is predicted by the ^{210}Pb accumulation rate, which was confirmed to be true from the ^{137}Cs activity profiles by Nittrouer *et al.* (1983/1984). A corollary is that if the observed and predicted depths of ^{137}Cs penetration agree, the effect of deep mixing on the ^{210}Pb accumulation rate is negligible. Table 3 compares the depths of ^{137}Cs predicted (H_p) from ^{210}Pb profiles and those actually observed (H_o) from Figure 3. Except for one core (station 8725), in gene-

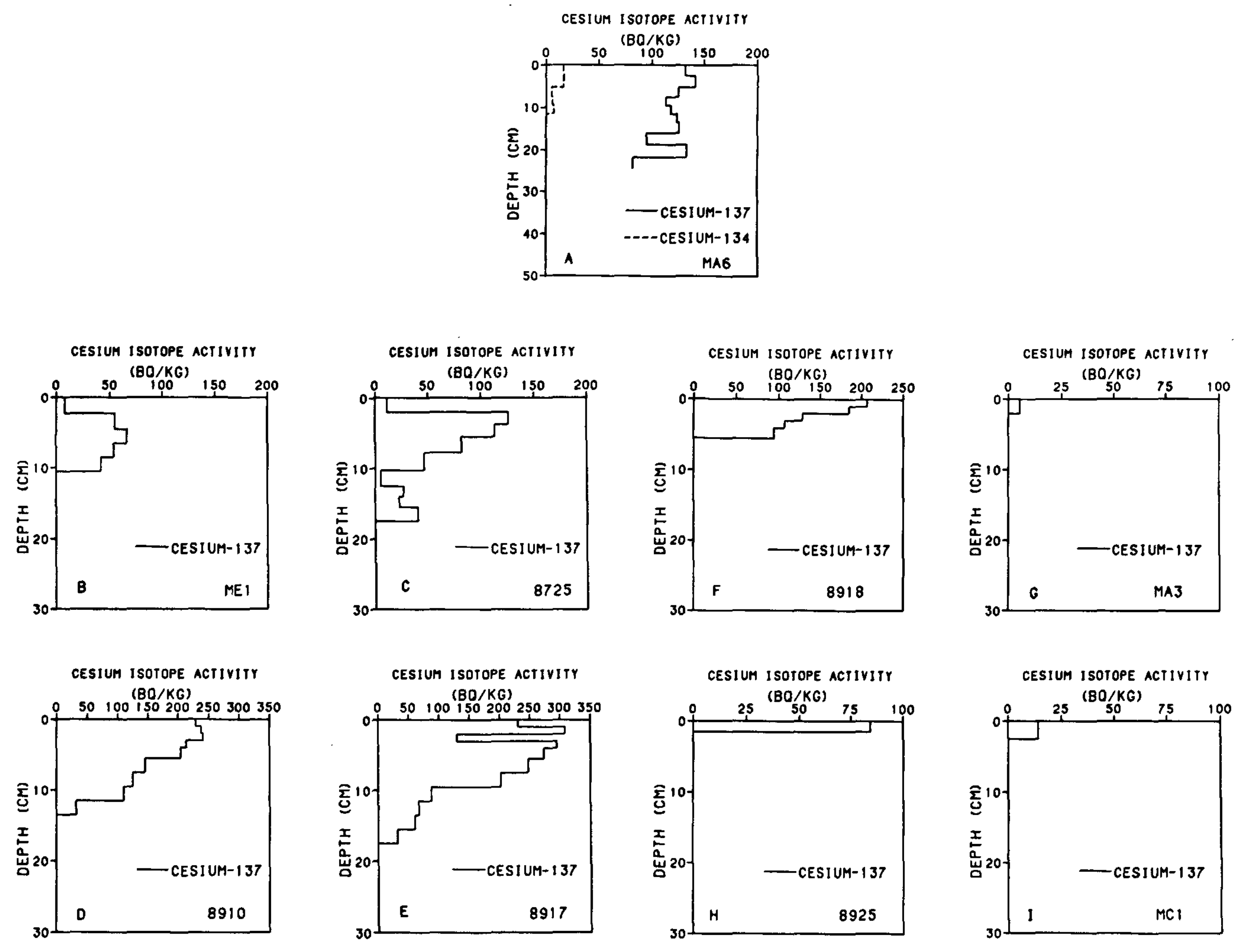

Figure 3

The activity-depth profiles of radiocesium isotopes in nine sediment cores.

ral, the agreement between H_p and H_o is good. Hence, deep mixing is not a common occurrence and ^{210}Pb accumulation rates calculated with the assumption of no deep mixing are accurate for most of the Gulf of Lions. This is true especially for the relatively deep water area because the observed depth of ^{137}Cs penetration in cores 8918, MA3, 8925 and MC1 (Fig. 3) would give independently very similar accumulation rates since the significant amount of ^{137}Cs occurred after 1952. Anderson *et al.* (1987) and Robbins and Edgington (1975) revealed that mixing and winnowing of sediments could cause redistribution of ^{137}Cs peak either downward or upward which was also observed in our ^{137}Cs profiles, while Davis *et al.* (1984) suggested that the shifting of the ^{137}Cs peak in sediments could be the result of transport of ^{137}Cs dissolved in pore waters.

From equation 5 (*see* above), using the observed ^{137}Cs penetration depth, H_p, and the ^{210}Pb accumulation rate, S, the mixing coefficient, D_B, can be estimated by rearranging equation 5:

$$D_B = (H_O - St)^2/2t \qquad (7)$$

The values of D_B in our cores ranged from 0.0001 to 2.08 $cm^2.yr^{-1}$ (Tab. 3) which are rather low figures. Guinasso and Schinck (1975) described a dimensionless parameter G, which is equal to the mixing rate (D_B/L) divided by the accumulation rate S. When G is high (>10), mixing dominates the effects of accumulation; while G is low (<1), the accumulation term dominates. In our sediment cores, G is generally low (Tab. 3) and except for station 8725, the values of G confirm that the ^{210}Pb apparent accumulation rates reflect the true rates of sedimentation in the Gulf of Lions. The relatively high figures of D_B (2.08 $cm^2.yr^{-1}$) and G (2.31) in core 8725 indicate that in this core there are some effects of relatively deep mixing compared to the other sediment cores.

The ^{134}Cs to ^{137}Cs isotope ratio in core MA6 is shown in Figure 4. The ratio (0.04-0.13) in the core MA6 decrease with depth to zero at a depth of 12 cm, which is similar to those found by Martin and Thomas (1990, 0.12-0.24) in the same area. In fact, the higher the ratio, the higher is the contribution of the most recent input. The activity of ^{137}Cs in our cores is clearly related to the distance from the river mouth and to the water depth. This distribution supports the hypothesis that in the area of river mouth the direct input from the atmosphere is less significant than the contribution from the river.

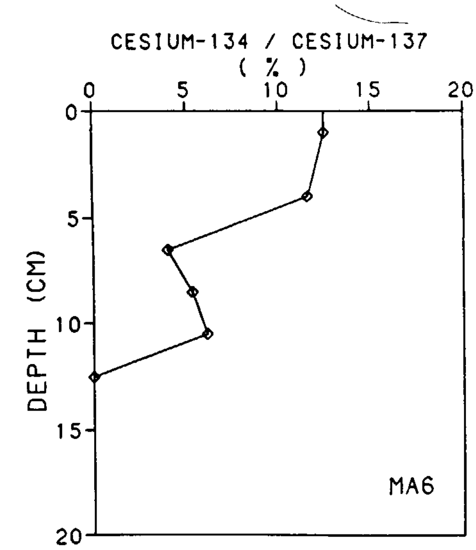

Figure 4

Variation profile of the isotope ratio (^{134}Cs to ^{137}Cs) at different sediment depths in core MA6.

Table 3

Comparison of predicted (Hp) and observed (Ho) ^{137}Cs penetration depth, mixing coefficients (DB) and the parametre G in the sediments.

Station	Collection date	^{210}Pb data		^{137}Cs penetration		Db	G
		Surface mixed layer L (cm)	Accumulation rate S ($cm.yr^{-1}$)	Hp (cm)	Ho (cm)	($cm^2.yr^{-1}$)	
MA6	1988	15	0,63	37	26*	0.22	0.02
ME1	1988	8	0,18	14	11	0.33	0.25
8725	1987	6	0.15	11	17	2.08	2.31
8910	1989	8	not measured		12		
8917	1989	8	0.20	15	17	1.33	0.83
8918	1989		0.12	4	5	0.006	
MA3	1988		0.02	1	1.5	0.009	
8 925	1989		0.03	1	1	0.0001	
MC1	1988		0.05	2	2	0.001	

* The core did not penetrate the ^{137}Cs layer due its limited length.

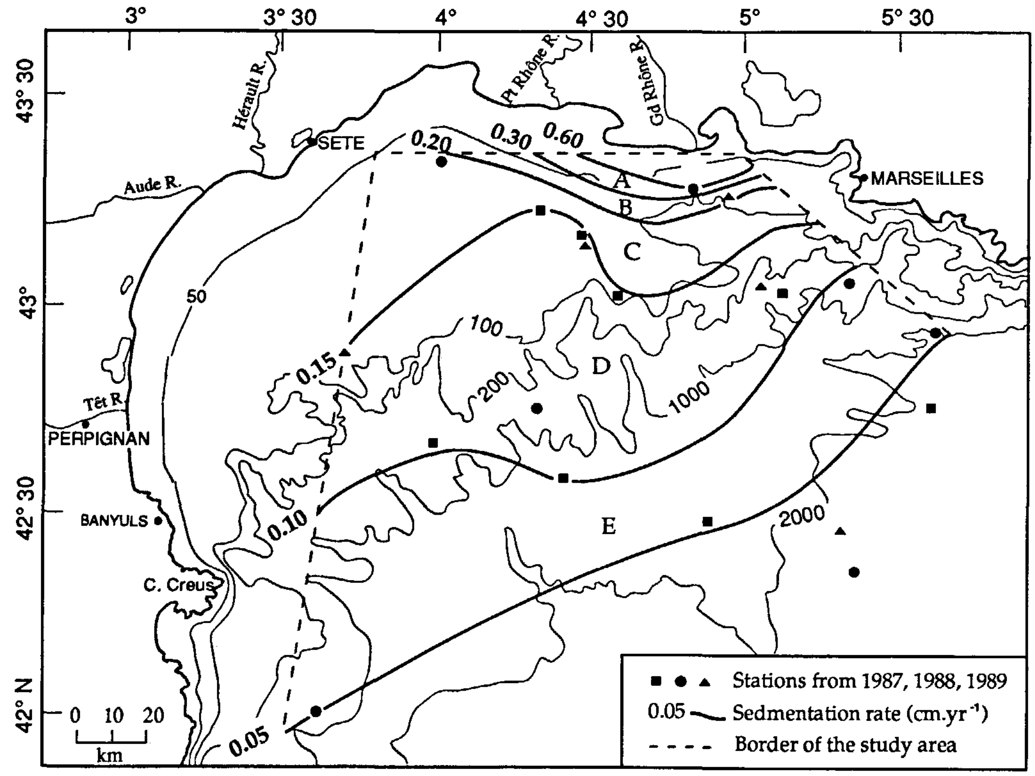

Figure 5

Spatial distribution of accumulation rates in the Gulf of Lions.

Sedimentation distribution

Figure 5 indicates a rough-like spatial distribution of ^{210}Pb apparent accumulation rates with a seaward decreasing gradient in the Gulf of Lions, which divides the studied area into five zones (A to E) by the isolines of sedimentation rate. Combining all isoline values and the corresponding isoline distances to the point of the highest isoline (0.6; Fig. 5) on a two-dimensional plot (Fig. 6), it is very clear that the distribution is nonlinear: the sedimentation rate drops sharply within the nearshore zone while the value decreases slowly further offshore. So the mean sedimentation rate (S_i) for each zone was calculated (Tab. 4), using an inverse square root (ISR) transformation to get a best fit of the curve by linearization according to the following formula

$$S_i = 1/\{\ [\ \sum_{i}^{i+1}\ (1/\sqrt{x_i})\ ]\ /2 \qquad (8)$$

where x_i = the sedimentation rate at isoline i (i = 1). This transformation prevents the overestimation of the mean sedimentation rate as compared to using simply the mean between two isolines. Taking this as a base together with an average sediment water content of 40 %, the maximum annual amount of the deposited sediment in each zone was estimated (Tab. 4).

In our study area, four depositional environments were observed:

1)- The Rhône prodeltaic area (zones A and B, Fig. 5) which is characterized by a strong contribution of the Rhone river. Sediment accumulation here is about 1.4 x 10^9 kg.yr^{-1}. Very near to river mouth, only one core (RT2) is available, with a limited length which is not considered representative for the estuarine area.

2)- The continental shelf area (zone C) in which erosion and resuspension often occur, fluxes being only indicative (Monaco *et al.*, 1990). Therefore, the figure of 2.8 x 10^9 kg.yr^{-1} is too high and is probably in reality much lower (in the order of 50 %).

3)- The continental slope area (zone D): in this region the depositional system is governed by both erosion and rapid transfer across the shelf and the upper canyon, and accumulation in the canyons (Courp and Monaco, 1990). The upper canyons in this area account for about 50 % of the slope surface which leads to a sedimentation of 2.9 x 10^9 kg.yr^{-1}.

4)- The upper fan area (zone E) dominated by accumulation with little sediment reworking processes.

Finally the total annual deposited amount of sediment in our study area becomes about 10.1 x 10^9 kg.yr^{-1} which

Table 4

Mean accumulation rate (S_i) for each zone and maximum deposited amount of sediments in the Gulf of Lions.

Site	Zone	Surface area (km^2)	S_i (ISR) (cm.yr^{-1})	R (g.cm^{-2}.yr^{-1})	Sediment accumulation 10^9 (kg.yr^{-1})
Rhône prodelta					
	A (0.60-0.30)	240	0.41	0.31	0.7
	B (0.30-0.20)	400	0.24	0.18	0.7
shelf					
	C (0.20-0.15)	2,200	0.17	0.13	2.8
slope					
	D (0.15-0.10)	6,500*	0.12	0.09	2.9
upper fan					
	E (0.10-0.05)	6,000	0.07	0.05	3.0
TOTAL		15,340			10.1

* only 50% of this area was taken into account, see text.

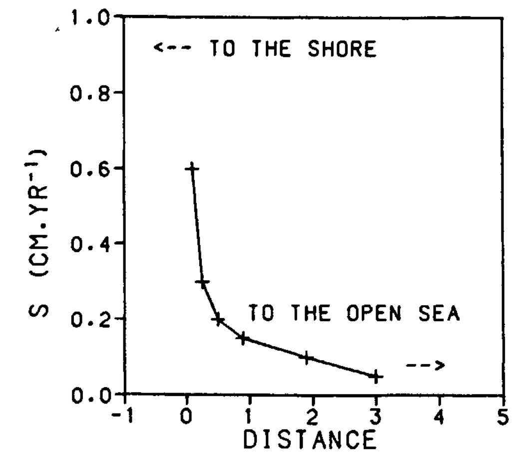

Figure 6

Variation curve of the isoline value (S) against the corresponding isoline distance to the position of the highest isoline (0.6), see Fig. 5.

Table 5

Estimations for sediment accumulation in the Gulf of Lions.

	Flux g. cm^{-2}.yr^{-1}	Accumulation 10^9 kg.yr^{-1}	%
The study area: 15,340 km^2			
River input (Rhone)		3-5*	30-50
Biogenic deposit	0.02**	3.1	30
Atmospheric deposit		2-4	20-40
Total deposition	0.05-0.31	10.1	

* *Pauc (1970); Blanc (1977) and Leveau and Coste (1987).*
** *Courp (1990) and Monaco* et al *(1990), see* text.

also includes the accumulation of biogenic production. Monaco *et al.* (1990) suggested that in the surface water there are two periods of maximum fluxes for biogenic constituents: one in summer with a strong contribution of organic carbon, carbonate and opal on both shelf and slope; and one in spring for opal which characterizes the fluxes over the slope. Their study of mass fluxes with a sediment trap in the western part of the Gulf of Lions (1990) indicated that the annual fecal pellet flux could become as high as 20 % of the total particle mass at the base of a 600 m water column, with an average flux of biogenic constituents of about 1100 mg.m^{-2}.d^{-1} which amounts to 0.04 g.cm^{-2}.yr^{-1}.

However, fluxes increase up to a factor of 6 from east to west in the Gulf of Lions (Courp, 1990). Therefore, we took the value of 0.02 g.cm^{-2}.yr^{-1} (50 % of the biogenic flux of the western part of the Gulf of Lions, Monaco *et al.*, 1990) which we consider as representative for the study area.The annual biogenic accumulation, assuming that no degradation or consumption ocurred, would become about 3.1 x 10^9 kg.yr^{-1} in the Gulf of Lions, leaving the deposit of about 2-4 x 10^9 kg.yr^{-1} to the atmospheric contribution which is in agreement with the number (4 x 10^9 kg.yr^{-1}) suggested by Martin *et al.* (1989), due to the annual discharge of the Rhone river (3-5 x 10^9 kg, Pauc, 1970; Blanc, 1977; Leveau and Coste, 1987; Tab. 5).

CONCLUSIONS

The ^{210}Pb analyses demonstrated the presence of surface mixed layers in the sediments of the nearshore area in the Gulf of Lions. Accumulation rates were determined by using the ^{210}Pb and ^{137}Cs dating methods. The agreement of ^{210}Pb and ^{137}Cs data indicates a general absence of deep mixing in the Gulf of Lions. Therefore, the apparent accumulation rates calculated from ^{210}Pb profiles (below the intensely surface mixed layer) generally reflect the true sedimentation rates.

The spatial distribution of deposition rates shows a seaward decrease in value, which suggests that a significant amount (30-45 %) of sediment supplied by the Rhône river is deposited on the river prodeltaic area and the remainder on the continental shelf and the slope in the study area.

The distribution of radiocesium activity confirms a strong contribution of sediment discharge by the Rhône river in the nearshore area. The annual deposited amount of sediment in this study area was estimated to be about 10.1 x 10^9 kg, of which some 3.1 x 10^9 kg.yr^{-1} is biogenic and where atmospheric input accounts for at least 20 % of the total amount of deposition. It can be concluded that in the last 100 years about 60 cm of sediment, or more, have been deposited in the shallow part of the Gulf of Lions with less than 100 m water depth, 10-15 cm on the shelf and the slope areas, and only 2-5 cm in the deeper part (> 2000 m) of the area.

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