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Estimation of sedimentation rates in the Bay of Mont Saint-Michel (France) by ^{210}Pb dating technique. A pilot study.

Tidal flats
Bay of Mont Saint-Michel
Sedimentation rates
^{210}Pb dating technique
^{137}Cs isotope

Zone infratidale
Baie du Mont Saint-Michel
Taux de sédimentation
Technique de datation au ^{210}Pb
Isotope ^{137}Cs

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ABSTRACT

Three cores taken in the tidal flat of the Bay of Mont Saint-Michel, were dated with two different methods, one involving use of the naturally-occurring isotope ^{210}Pb, the other using a man-made ^{137}Cs isotope. For two of the cores it was possible to calculate sedimentation rates. In these cores the data obtained with the two different methods agreed well: sedimentation rates of 0.39 ± 0.08 (^{210}Pb method) resp. 0.48 cm.y^{-1} (^{137}Cs method) were found in one core; and of 0.47 ± 0.07 and 0.4 0 cm.y^{-1} in the other. In the third core no reliable sedimentation rate could be calculated, although the Cs data indicate that the sedimentation rate is in the order of 5 cm per year. These data are in good agreement with sedimentation estimates based on cartographical data and comparison of successive aerial photographic surveys.

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RÉSUMÉ

Estimation de taux de sédimentation dans la baie du Mont Saint-Michel (France) par analyse du ^{210}Pb. Une étude expérimentale

Trois carottes prélevées dans la zone infratidale de la baie du Mont Saint-Michel ont été datées par deux méthodes différentes : par l'utilisation des radioéléments naturel ^{210}Pb et artificiel ^{137}Cs. Pour deux des carottes analysées, il a été possible de calculer des taux de sédimetation. Dans les deux cas, les données obtenues avec les différentes méthodes sont comparables, les taux de sédimentation étant de 0,39 et 0,47 cm.a^{-1} pour le premier prélèvement et 0,47 et 0,4 cm.a^{-1} pour le second, basés respectivement sur les méthodes de datation au ^{210}Pb et au ^{137}Cs. Dans le troisième prélèvement, aucun des taux de sédimentation ne peut être précisément calculé ; toutefois les données du ^{137}Cs indiquent un taux de l'ordre de 5 cm.a^{-1}. Ces données sont conformes avec les estimations de sédimentation basées sur la comparaison de documents cartographiques et des clichés successifs de photographie aérienne.

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INTRODUCTION

The objectives of this study were to date recent tidal flat sediments from different environments in the bay of Mont Saint-Michel and to interpret and evaluate the extent to which sedimentation rate is influenced by local variations of hydrodynamics, geomorphology and biology.

As a dating technique we used the isotopes ^{210}Pb and ^{137}Cs. Sedimentation rates in this area have been estimated in previous studies (Doulcier, 1977; Fetter-Turtaud, 1981; Nikodic, 1981), on the basis of:

- comparison of topographic surveys or bathymetrical maps of the same area, established at different times; and
- hydrological measurements which result in calculation of volumes of suspended matter.

Such estimations are limited by the fact that they do not differentiate between subsequent sedimentation and erosion: only the net effect can be measured. The use of ^{210}Pb for geochronology was first suggested by Goldberg (1963). Its 22.3 year half-life makes this isotope a powerful tool in studying sedimentation processes. ^{137}Cs ($T1/2 = 30$ y) and ^{134}Cs ($T1/2 = 2.06$ y) are man-made radio-isotopes and were introduced in the marine environment by the testing of nuclear weapons in the 1950s and early 1960s, and by the Chernobyl accident in 1986.

STUDY AREA

The bay of Mont Saint-Michel (500 km^2), located at the southern end of the Norman-Breton gulf, experiences one of the highest tidal ranges in the world (up to 15 m). The resulting strong tidal currents, in combination with local west-dominated winds, generate a high energy environment displaying a large variety of sediment types and patterns (Larsonneur, 1989; Caline *et al.*, 1982). The superficial sediments are distributed according to two main grain-size gradients. Firstly, an overall landward-fining gradient which reflects the gradual decrease of tidal current velocity from open marine to upper tidal zones. Secondly, a group of smaller scale gradients are locally superimposed on this regional gradient, and are related to sedimentary units such as subtidal bioclastic shoals, intertidal annelid reefs, migrating tidal channels or supratidal shell ridges.

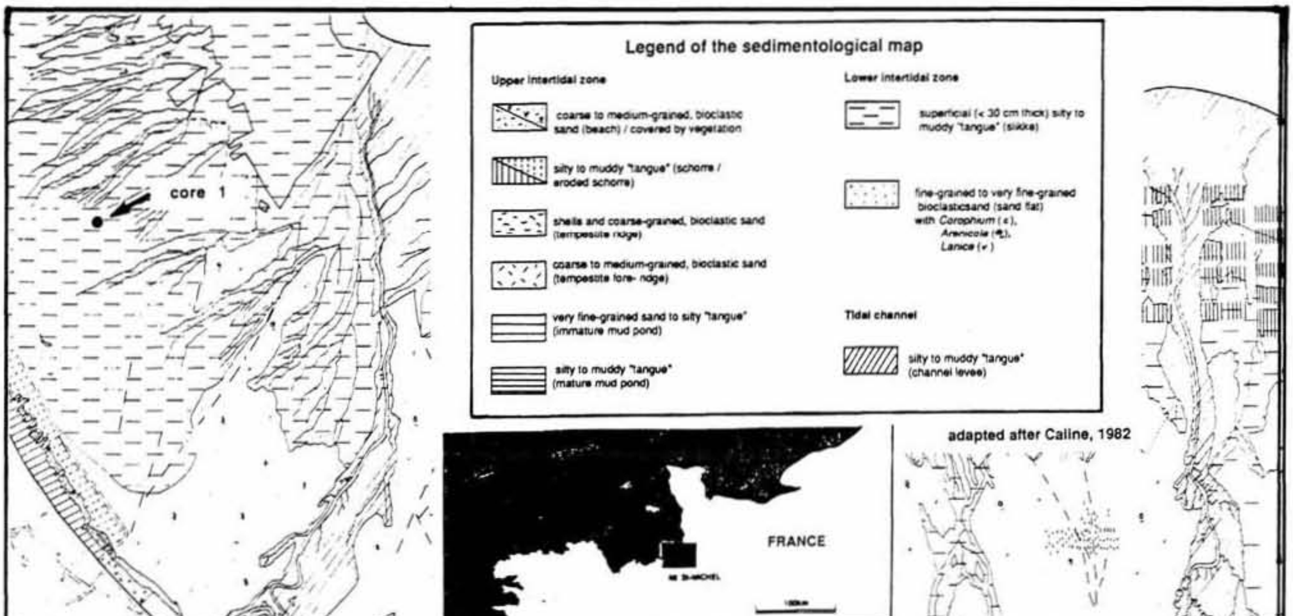

Figure 1

Location of the three cored samples on the sedimentalogical map of the western domain of the bay of Mont Saint-Michel.

Localisation des trois carottes dans leur contexte sédimentologique de la zone ouest de la baie du Mont Saint-Michel.

Table 1

Results cores Mt. St. Michel.

Résultats des carottes du Mont Saint-Michel.

	Core 1	**Core 3**	**Core 6**
Sed. rate ^{210}Pb (cm y^{-1})	0.39 ± 0.08	> 1	0.47 ± 0.07
Sed.rate ^{137}Cs (cm y^{-1})	0.48	> 1	0.40

The sediments are characterized by an anomalously high carbonate fraction for temperate tidal deposits. The carbonate fraction consists of biogenic particles which form through the break-up of mollusc shells and calcareous microflora.

From a physiographical viewpoint, the intertidal bay comprises two juxtaposed domains. The eastern area displays typical features of an estuarine complex exposed to strong alternating tidal currents. The western domain forms a wide tidal flat, gradually changing from a mud flat (bay of Cancale) into a sand flat (bay of Cherrueix).

In this area, sedimentation is controlled by both rotating and alternating tidal current patterns.

SAMPLE LOCATION

The three cores dated came from the upper zone of the tidal flat in the western domain of the bay of Mont Saint-Michel (Fig.1).

The three shallow cores (30 cm long, 9 cm diameter) were taken in June 1987 from different sub-environments: each of them being characterized by active recent sedimentation (Caline, 1982).

Core 1 (Fig. 1)

It is located in the middle tidal zone (slikke) of the bay of Cancale. This slikke consists of a uniform mud flat with large patches of freshly deposited mud, cut by a dendroform network of shallow gullies, active during the ebb period.

The development of a mud flat in the bay of Cancale results from a combination of:

- a wind-protected area due to the outcropping basement of the "Massif de Saint-Malo" which forms 60 m high cliffs outlining the western border of the bay;
- weak tidal currents with a gyratory pattern whereas the currents have a marked alternative pattern elsewhere in the bay (Fig. 1);
- biodeposition of mud by oyster banks. The natural subtidal oyster banks have now been replaced by oysters which are intensively cultivated in the intertidal flat. It should be noted that the installations (tables, alignment of posts) contribute to attenuate the current velocity and therefore increase the mud deposition.

Table 2

^{210}Pb, ^{226}Ra and ^{137}Cs data.

Teneurs en ^{210}Pb, ^{226}Ra et ^{137}Cs.

Core #1 **(average ^{210}Pb supported = 9.2 Bq kg^{-1})**

Depth (cm)	^{210}Pb exc. (Bq.kg^{-1})	^{137}Cs (Bq.kg^{-1})	^{226}Ra (Bq.kg^{-1})
0.25	49.8 ± 2.3	16.0 ± 3.3	9.9 ± 1.0
0.75	69.0 ± 3.0		
1.25	51.0 ± 2.3	17.2 ± 3.1	9.2 ± .9
1.75	54.8 ± 2.5		
2.25	66.5 ± 2.7	19.1 ± 5.0	8.3 ± .8
2.75	59.2 ± 2.8		
3.25	62.2 ± 3.0	22.0 ± 4.1	
3.75	62.0 ± 3.0		
4.25	67.0 ± 3.2	16.1 ± 2.9	9.1 ± .9
5.5	44.8 ± 1.8		
6.5	54.2 ± 2.0	13.1 ± 1.5	
8.5	41.2 ± 1.8		
10.5	34.7 ± 1.7		
11.5	38.3 ± 2.7	14.4 ± 2.8	9.3 ± .9
12.5	35.2 ± 2.8		
13.5	33.2 ± 2.8	< 2	
17.5	18.0 ± 2.5		
18.5	0.0 ± 1.5	< 2	

Core #3 **(average ^{210}Pb supported = 16 Bq kg^{-1})**

Depth (cm)	^{210}Pb exc. (Bq.kg^{-1})	^{137}Cs (Bq.kg^{-1})	^{226}Ra (Bq.kg^{-1})
0.5	33.0 ± 1.7	13.1 ± 2.0	17 ± 2
1.5	27.0 ±1.5	10.3 ± 2.8	
2.5	27.0 ± 1.3	9.0 ± 1.4	
3.5	32.8 ± 1.7		
4.5	37.3 ± 2.8	16.7 ± 3.7	13 ± 1
6.5	52.3 ± 3.0	19.6 ± 2.0	
8.5	51.5 ± 3.0	19.0 ± 1.4	
13.5	46.7 ± 2.8	11.7 ± 1.6	
15.5	52.2 ± 3.0	17.6 ± 1.5	
17.5	33.3 ± 2.3	14.0 ± 1.1	15 ± 1
20.5	35.5 ± 2.3	13.5 ± 1.1	
24.5	41.8 ± 2.5		
26.0	39.3 ± 2.5	15.4 ± 1.1	18 ± 2

Core #6 **(average ^{210}Pb supported =15 Bq kg^{-1})**

Depth (cm)	^{210}Pb exc. (Bq.kg^{-1})	^{137}Cs (Bq.kg^{-1})	^{226}Ra (Bq.kg^{-1})
0.5	38.0 ± 1.8		15 ± 1
1.5	27.0 ± 1.2	11.9 ± 1.4	17 ± 2
2.5	30.8 ± 1.3		
3.5	29.2 ± 1.2	10.3 ± 1.2	18 ± 2
4.5	25.2 ± 2.2		
5.5	27.3 ± 2.5	9.0 ± 1.0	11 ± 1
6.5	22.7 ± 2.3		
7.5	22.7 ± 2.3	6.5 ± 1.5	
8.5	22.7 ± 1.5		14 ± 1
9.5		11.4 ± .9	
10.5	20.3 ± 1.2		
11.5	23.0 ± 1.5	10.9 ± 1.4	
12.5	18.7 ± 1.2		
13.5	19.8 ± 1.0	7.8 ± 1.3	
14.5	17.7 ± 1.0		
15.5	11.0 ± .7	5.1 ± .9	
16.5	.7 ± 1.0	< 2	

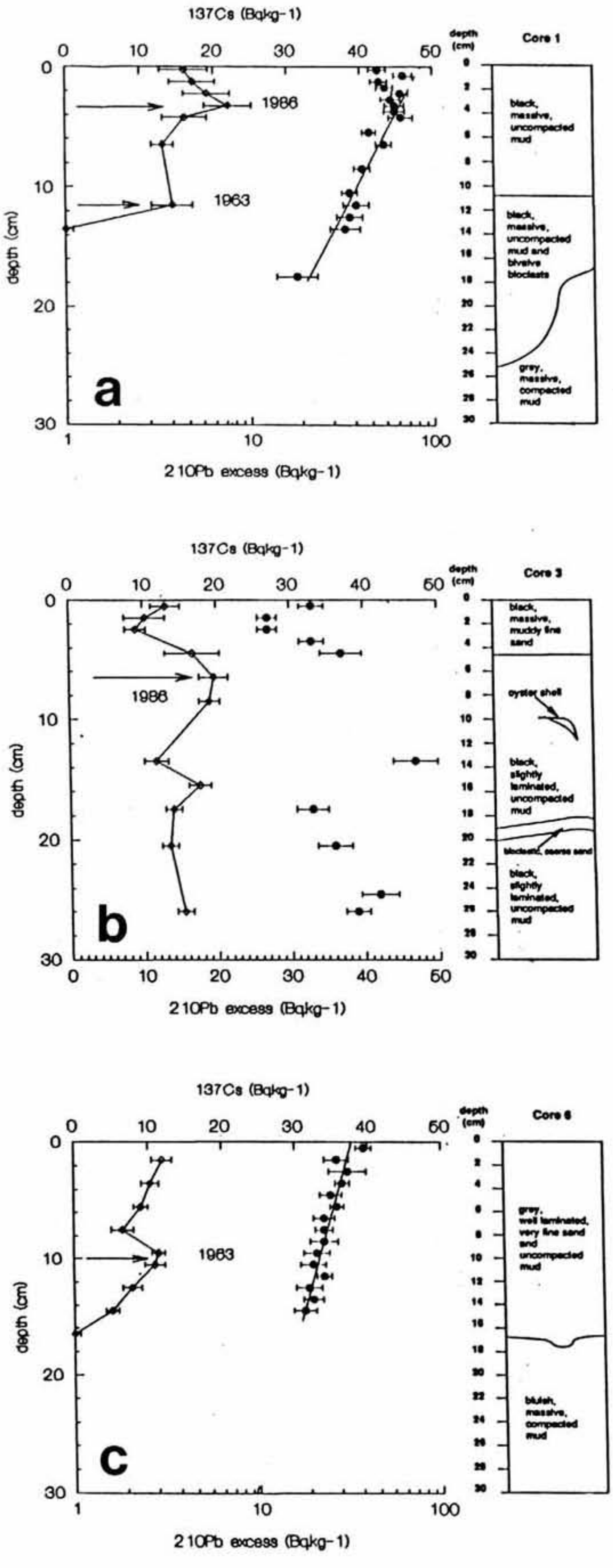

Figure 2

Core description, ^{210}Pb exc. and cesium concentrations versus depth of core 1, 3 and 6.

Description des carottes, activité du ^{210}Pb exc. et du césium.

Core 3 (Fig. 1)

It is located in a ridge-protected mud flat of the upper tidal zone, which developed behind an alignment of shell ridges. The ridge-protected mud flats form very active deposition cells controlled by the migration of shell ridges both landwards (by storm action combined with spring tidal currents) and westwards (by swell and tidal current diffraction). These mud ponds are exposed to long periods of emersion during summer time (mud cracks develop) and show cyclic development of benthic diatom colonies (algae bloom). The constant rise of the mud pond level is indicated by the steady seaward progression of the salt marsh vegetation.

Core 6 (Fig. 1)

It is located on the edge of a meandering, secondary tidal channel. This channel is connected to the main distributary channel of Saint-Benoît-des-Ondes which collects the marsh waters of the "Marais de Dol". The bottom of these channels is made up of compacted, bluish mud locally bored by colonies of pholads.

METHODOLOGY

^{210}Pb dating

^{210}Pb (half-life 22.3 y) is a member of the ^{238}U-decay series. There are two major sources of its presence in the marine environment: *in situ* radioactive decay of ^{226}Ra (supported ^{210}Pb); and production and subsequent deposition and adsorption of ^{222}Rn-produced atmospheric ^{210}Pb.

^{210}Pb exc. is the total amount of ^{210}Pb in the sediment minus the supported amount. The supported amount can be calculated by measuring the ^{226}Ra concentration in the same sample (Tab. 2). This was done by the method according to Mathieu *et al.*. (1980). Sedimentation rates were calculated according to the CIC (Constant Initial Concentration) method (Robbins and Edgington, 1975, Goldberg *et al.*, 1977), using the equation

$T_i = y^{-1}.\ln(A_o/A_i)$ in which

y = decay constant of ^{210}Pb ($0.03114\ y^{-1}$) A_0 = unsupported ^{210}Pb activity at depth A_o;

A_i =unsupported ^{210}Pb activity at depth A_i;

T_i =difference in ages of sediment at level A_o and A_i in years.

^{210}Pb activity was measured *via* its granddaughter ^{210}Po, which is assumed to be in secular radioactive equilibrium (Goldberg, 1963).

Samples were dried, homogenized, spiked with a known amount of ^{208}Po as a yield determinant and leached with hot concentrated acids according to standard procedures (Flynn, 1968). Polonium isotopes were plated on a silver disc at 90° C after reduction of Fe^{3+} with ascorbic acid and analysed by alpha spectrometry.

The precision of the ^{210}Pb activity measurement is 5 % or better, based on counting statistics only. The total chemical yield was in general 90 % or more.

^{137}cesium measurements

Cesium was measured by low background gamma spectrometry. There are two major sources for ^{137}Cs ($T_{1/2}$=30 y) in the marine environment: fallout produced by nuclear weapons tests in the 1950s and early 1960s, which was at its maximum in 1963; andnuclides liberated by the accident at the nuclear power station at Chernobyl on 26 April 1986. The radioactive waste travelled to Western Europe with lower tropospheric air masses and reached Paris on 30 April, southern England on May 2, the southern North Sea on 3 May. Rainfall was the major pathway of deposited activity (Kempe and Nies, 1987).

Since the time between our cesium measurements and the Chernobyl accident is more than two years, the ^{134}Cs ($T_{1/2}$ = 2.06 y) concentrations are close to or below our detection limit (± 1 $Bq.kg^{-1}$). ^{134}Cs (measured at the 604.7 and 795.8 KeV lines) was detectable at only one horizon in each core, coinciding with the ^{137}Cs maximum attributed to the Chernobyl fallout.

RESULTS AND DISCUSSION

^{210}Pb, ^{226}Ra, ^{134}Cs and ^{137}Cs data are given in Table 2, Table 3 and Figure 2. The resulting sedimentation rates are summarized in Table 1.

Core 1

It shows an exponential decrease of ^{210}Pb with depth (Fig. 2).

For this core the sedimentation rate as calculated from the ^{210}Pb data is 0.39 ± 0.08 $cm.y^{-1}$.

The ^{137}Cs data (Fig. 2) agree well with this. The ^{137}Cs maximum of 1963 is found at 11.5 cm depth which yields a sedimentation rate o f 0.48 $cm.y^{-1}$.

The ^{210}Pb profile shows a bioturbated layer of 4.5 cm thickness. These data have been omitted in the sedimentation rate calculation for this core.

If we assume a sedimentation rate of 0.4 $cm.y^{-1}$, the cesium related to the Chernobyl accident should be found at 0.5 cm depth. This maximum is found at 3.25 cm depth.

Table 3

^{134}Cs activities, corrected for decay back to 1 May 1986.

Teneurs en ^{134}Cs (valeurs 1er mai 1986).

Core	Depth (cm)	Concentration ($Bq.kg^{-1}$)
1	3.25	3.0 ± 2.7
3	6.5	1.6 ± 1.2
6	1.5	3.5 ± 3.0

Possible explanations are:

1) Post-depositional mobilization and downward transportation of cesium, especially in anoxic sediments, found by Comans *et al.* (1989).

2) Bonnett *et al.* (1988) found ^{137}Cs activities in the finest fraction (< 2 µm) 5-7 times higher than in the coarser (> 62.5 µm) fraction.

Unfortunately, grain-size variations cannot be taken into account since relevant data are not available.

Core 3

The data from core 3 are more difficult to interprete. The ^{210}Pb profile is very irregular (Fig. 2) and a sedimentation rate cannot be calculated. Unsupported ^{210}Pb can be found to a depth of up to 30 cm, which means that this sediment is relatively young and that at this location the sedimentation rate is high.

The core seems to be too short to show the ^{137}Cs fallout peak related to the year 1963, which means that the sedimentation rate is more than 1 $cm.y^{-1}$. The Cs profile shows a maximum at 6 cm. At this horizon there is a weak ^{134}Cs signal, which must be related to fallout from Chernobyl, resulting in a sedimentation rate of a few centimetres per year.

Comparison of successive aerial photograph surveys (aerial surveys between 1969 and 1986 made by the *Institut Géographique National*) show that this mud pond is twelve years (± 2 years) old. The sedimentation rate is therefore ranging from 2.5 to 5 $cm.y^{-1}$.

Core 6

This core displays characteristics similar to those of core 1: it shows an exponential decrease of ^{210}Pb with depth (Fig. 2).

For this core the sedimentation rate as calculated from the ^{210}Pb profile is 0.47 ± 0.07 $cm.y^{-1}$.

The ^{137}Cs peak related to the year 1963 is found at a depth of 9.5 cm, resulting in a sedimentation rate of 0.40 $cm.y^{-1}$. This core is well-laminated and unlike core 1, the ^{210}Pb and ^{137}Cs profiles indicate that bioturbation does not play an important role in this core. This is confirmed by the cesium profile. ^{134}Cs and ^{137}Cs, related to the Chernobyl accident, are found in the top few centimetres.

CONCLUSIONS AND IMPLICATIONS

The ^{210}Pb dating technique, especially in combination with Cs measurements, is an attractive method of assessing rates of deposition in modern tidal environments.

This pilot study shows that the ^{210}Pb-derived sedimentation rates (0.4 to 5 $cm.y^{-1}$) are within the range of previous regional estimates. Long term sedimentation rates (since 1829), based on cartographical data, show sedimentation rates of around 0.45 $cm.y^{-1}$ in this part of the bay (Larsonneur, 1989).

For a meaningful estimation of the regional rate of sedimentation using ^{210}Pb dating, the integration of a large number of cored samples from both active sedimentation and erosion areas is recommended.

Reliable assessement of the rate of sedimentation has major implications for:

- civil engineering works in macrotidal environments (*e.g.* preservation of the insularity of the Mont Saint-Michel);
- improvement of paleoenvironmental reconstruction and geological basin modelling.

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