Use of axial tomography to follow temporal changes of benthic communities in an unstable sedimentary environment (Baie des Ha! Ha!, Saguenay Fjord)

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Abstract

In the upper layer of the sediment column, organic matter recycling is greatly influenced by bioturbation. However, there are many physical changes in the nature of the sediment that may disturb benthic communities and create a biogeochemical imbalance. Following a very heavy rainfall between 26 and 29 July 1996, an intense flash flood in the Saguenay Fjord caused discharges of 6 million cubic metres of sediments into Baie des Ha! Ha!. Unstable sediment deposits located at the top of the delta of the Rivière des Ha! Ha! were sporadically exported to the deep basin. After this physical disturbance, meiobenthic and macrobenthic organisms progressively re-colonised the sediment column. To determine the impacts of such sedimentary depositions on benthic fauna, two stations, one at the head and one at the mouth of the Baie des Ha! Ha!, have been monitored since 1996. During this survey, we developed a new method for the quantification of biogenic structures using computer axial tomography (CAT-Scan). Benthic fauna analysis showed that the two stations were characterised by different temporal changes in the benthic dynamics according to their geographic location. Using CAT-Scan analysis of sediment cores, we were able to characterise the stability of the sediment column for the two stations in 1999 and 2000. Scan results suggest that

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colonisation processes were closely linked with the stability of the sediment column. Erosion and re-deposition of surficial sediments caused a succession in the formation of biogenic structures. These variations were characterised for the first time using CAT-Scan, which is a nondestructive, rapid, and precise method. Tomographic analysis showed the importance of the production and destruction rates of biogenic structures and the sedimentation rate for the preservation of burrows and potentially reactive components. This study finally demonstrated that each erosional event could be followed by a rapid formation of biogenic structures, allowing the re-oxidation of old deposits.

Keywords: Benthic communities; Biogenic structures; Bioturbation; Computer axial tomography; Large-scale disturbance

1. Introduction

Sedimentary events such as erosion, transport, and massive deposition of soft sediment represent major sources of disturbance for sediments and benthic communities and may temporarily disturb the biogeochemical functioning of the sediment column (Thistle et al., 1985; Aller, 1989; Aller and Stupakoff, 1996; Deflandre et al., 2002). These sedimentary events occur with variable intensities in intertidal environments (Yeo and Risk, 1979; Desrosiers et al., 1984), on continental slopes, and in the abyssal plain (Gage et al., 1990; Stora et al., 1999). The Saguenay area (Quebec, Canada) has been the locus of many natural seismic and sedimentary disasters (Schafer et al., 1980; Locat and Leroueil, 1988; du Berger et al., 1991; Urgelès et al., 2002). In July 1996, unexpected heavy rains caused an exceptional flash flood in many rivers of the Saguenay area, particularly the Rivière des Ha! Ha! at the head of Baie des Ha! Ha! (Yu et al., 1997; Pelletier et al., 1999a). More than 6×10^6 m^3 of sediments and debris were carried into Baie des Ha! Ha! in a few hours (Pelletier et al., 1999b). Clean, newly deposited flood sediments buried the old contaminated ones, thus providing a natural capping layer (Pelletier et al., 1999b; Maurice et al., 2000).

Following this type of disturbance, benthic organisms rapidly re-colonise the sediment column (Pearson and Rosenberg, 1978; Rhoads and Germano, 1982; Aller, 1989). Benthic activities (burrowing, feeding, and respiration) are known to modify the physical, chemical, and biological properties of sediment (Rhoads et al., 1978; Aller, 1982). Biological sediment reworking by macrofauna and meiofauna changes the sediment's primary structure (Rhoads and Young, 1970; Krantzberg, 1985; Nerhing et al., 1990; Gérino, 1992; Tita et al., 2001; François et al., 2002). The modification of sediment geochemistry through bioirrigation also affects sediment microbial processes (Aller and Aller, 1986; Krantzberg, 1985; Aller and Aller, 1998; Gilbert et al., 1998). These bioturbation processes are particularly characterised by biogenic structures in consolidated sediments (Rhoads and Boyer, 1982; Gérino, 1992) that can greatly influence organic matter recycling (Rhoads, 1974; Aller and Aller, 1986; Jones et al., 1994; Coleman and Williams, 2002).

Even though one-dimensional sediment reworking has been well quantified by appropriate tracers and models (Gérino et al., 1998; François et al., 2002), it is difficult

to quantify biogenic structures in marine sediments (Gérino, 1992). Previous studies attempted to visualise and quantify biogenic structures, for example, using resin casts (Risk et al., 1978; Gérino, 1992) and planar radiography (Aller, 1989; Kuehl et al., 1995; Aller and Stupakoff, 1996; Gérino et al., 1999). These methods were often limited to qualitative analyses and could not quantitatively measure the extent of burrows with accuracy: resin casts do not identify relict burrows, which create microenvironments, and planar radiography do not identify structures perpendicular to the plane of observation, overlapping structures, nor the smallest structures.

Recently, the use of computer axial tomography (CAT-Scan) in benthic ecology has led to much more precise images of sediment cores that have allowed the quantification of biogenic structures within transversal sediment sections (de Montety et al., 2000; Michaud et al., 2001; Mermillot-Blondin et al., submitted for publication). CAT-Scan imaging allows the characterisation of sedimentary facies (Wellington and Vinegar, 1987; Kenter, 1989; Long and Ross, 1991; Orsi et al., 1994; Boespflug et al., 1995). Crémer et al. (2002) used this method in the Saguenay Fjord following the 1996 flood to investigate the mode of massive sediment deposits and the potential for re-mobilisation of these deposits; in sediment cores taken in 1998, CAT-Scan detected a significant reworking of the superficial sediments in direct relation with bioturbation. Using samples taken in 1999, de Montety et al. (2000) tested and improved the CAT-Scan method as a tool to monitor changes in benthic ecology by quantifying biogenic structures in the Saguenay Fjord.

The main objective of this study was to use the CAT-Scan method to study the dynamic evolution of biogenic structures in the Baie des Ha! Ha! between 1999 and 2000 in relation to physical disturbances of the sediments (e.g., erosion).

2. Materials and methods

2.1. The study area

Baie des Ha! Ha! is located in the upper part of the Saguenay Fjord (Fig. 1). The Baie des Ha! Ha! drainage basin is oriented north–south and has an area of 608 km^2. Two small rivers, the Mars and the Ha!Ha!, flow near the head of the bay. The delta of Ha!Ha! River within the bay is a sub-boreal type and is subjected to frequent landslides and river discharge events (Schafer et al., 1980). The Rivière des Ha! Ha! had been heavily affected by the sediment discharges of the July 1996 flash flood due to the very heavy rain following intense climatic perturbations and the bursting of the Ha! Ha! River dam breakdown. The dam, located 35 km from the mouth of the bay, drained 26 million cubic metres into the bay in 18 h (Pelletier et al., 1999a). During this event, more than 6×10^6 m^3 of sediments and debris were carried onto the intertidal Ha!Ha! River delta and accumulated sporadically over less than 2 days in the deep basin (Lapointe et al., 1998). This new sedimentary deposit layer covered the entire bay area in variable thicknesses, depending on the station location (Pelletier et al., 1999b; de Montety et al., 2000; Urgelès et al., 2002). Stations 2 and 13, located at the head (85 m depth) and at the mouth (125 m depth) of the bay (Fig. 1), respectively, represented the proximal and distal limits of the

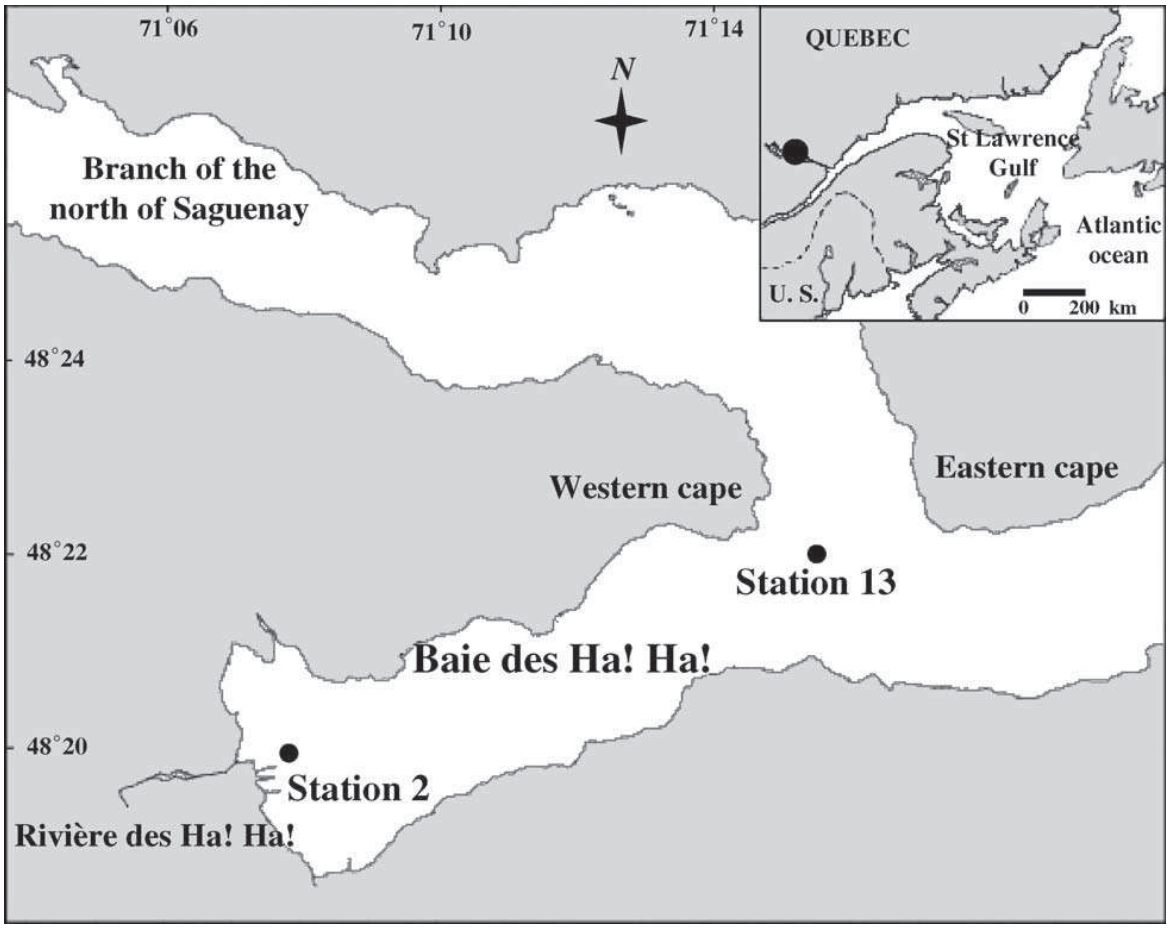

Fig. 1. Study site in Baie des Ha! Ha! (Saguenay Fjord, Quebec, Canada).

deltaic environments to observe changes induced by the new 1996 layer (Pelletier et al., 1999b).

2.2. Macrofauna sampling

To determine macrobenthic densities for each station, three sediment samples were taken with a Van Veen grab (1/8 m^2) during May every year from 1997 to 2000. Samples were sieved on a 1-mm grid to extract macrofauna. Each sample was kept in formaldehyde (4%). Macrobenthic organisms were sorted, counted, and identified to the species level.

2.3. Core sampling

An USNEL box corer (0.5 m^2) provided us with four sediment cores ($H = 40$ cm; I.D. = 15 cm) for each station at the same time as the faunal samples. Three cores were used to study the vertical distribution of the benthic fauna (de Montety et al., submitted for publication) and one core was scanned to quantify biogenic structures. Core tops were sealed with a paraffin plug to preserve the water–sediment interface and the biogenic structures. Cores were stored in a cold room before CAT-Scan analysis.

2.4. Axial tomography analysis

CAT-Scan was originally designed for medical applications (Hounsfield, 1973; Kantzas et al., 1992) as a nondestructive technique for the investigation of internal structures of human bodies. It is now applied to a variety of nonmedical fields (Duliu, 1999). CAT-Scan has been adapted by geologists (Wellington and Vinegar, 1987; Kenter, 1989; Long and Ross, 1991; Orsi et al., 1994; Boespflug et al., 1995; Crémer et al., 2002) to characterise sedimentary facies in marine sediments.

In preparation for the analysis, the core is positioned on a bed that slides through a gantry (Fig. 2). The gantry is made up of an X-ray source that is opposite from 600 receptors. The receptor–source system rotates around the sample in a short period of time (2 s for one image). This helical rotation allows the measurement of the X-ray attenuation through the core at many different angles (Wellington and Vinegar, 1987). X-ray beams are attenuated through the matter following the Beer–Lambert law:

$$I = I_0 e^{-\mu x} \tag{1}$$

where I_0, I, and x are the initial intensity of the X-ray incident beam, the measured attenuated intensity on the detectors, and the sample thickness, respectively. The parameter μ is the linear attenuation coefficient depending on both the atomic number and the density of the investigated object (Boespflug et al., 1994).

By determining the numerical value of this coefficient for any point of the core, a significant amount of information concerning the sample density could be obtained. For

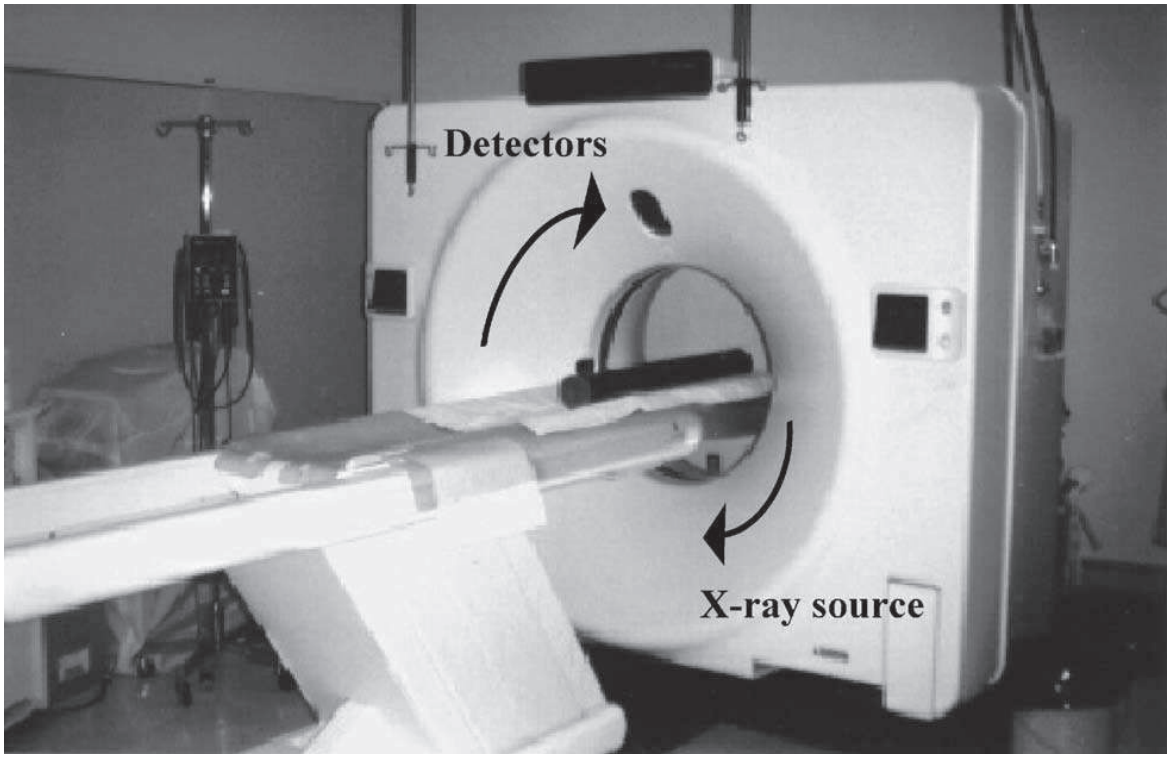

Fig. 2. Computer axial tomograph (CAT-Scan).

relatively homogeneous marine sediments, this coefficient is expressed in Hounsfield units (HU) or tomographic intensities (TI) (Hounsfield, 1973):

$$\mathrm{TI} = \left(\frac{\mu_s}{\mu_w} - 1\right) \times 1000 \tag{2}$$

The linear attenuation coefficient of the sample (μ_s) is compared with the water density (μ_w). A specific density value is attributed to each tomographic intensity (Table 1). Tomographic density values are a function of mineralogy, grain size, and sediment compaction (Kenter, 1989; Boespflug et al., 1995).

Reconstruction of the distribution function of the linear attenuation coefficient was computerised and used to obtain CAT-Scan images following any chosen section (Boespflug et al., 1994). We used a medical imagery treatment software, Osiris (Ligier et al., 1994), to visualise sedimentary and biogenic structures. For image display, TI values were represented on a scale of grey. This grey scale is a function of 4096 values, with 1 value per pixel. Pixel tones were inversely correlated with attenuation value. Darker zones represented lower X-ray attenuation and lighter zones represented higher ones (Boespflug et al., 1994).

For each sampled sediment core, a median longitudinal section was made using a source radiation of 120 kV and an intensity of 40 mA. This image had a pixel resolution of 0.5×0.5 mm. To quantify biogenic structures, transverse sections were obtained with a thickness of 5 mm from the zero level (i.e., determined at the sediment–water interface) down to 50 cm, giving 100 slices per core. Transverse sections had a pixel resolution of 0.25×0.25 mm.

The Osiris software (Ligier et al., 1994) allowed us to determine the tomographic intensity of each pixel in longitudinal and transversal images. For each median longitudinal profile, we determined the tomographic intensities with depth (tomogram) that gave information about the nature of sedimentary facies. For each transversal slice, the Osiris software plotted the number of pixels with the tomographic intensities (Fig. 3). The TI limit value between biogenic structure and sediment structure was represented by tomographic intensities of less visible biogenic structures. The TI associated with the biogenic structures was calculated from five arbitrary points in five less visible biogenic structures (Fig. 3). The average of these 25 points gave the maximal mean TI value attributed to biogenic structures in each transversal slice. Knowing the number of pixels that were lower and higher than the maximal intensity threshold corresponding to biogenic structures, it was possible to calculate the percentage of space occupied by the biogenic

Table 1
Relations between sample density values and sample tomographic intensity values (TI) (modified from Boespflug et al., 1994)

	Sample composition			
	Air	Water	Quartz	Calcite
Density (mg/m^3)	0	1	2.67	3
Tomographic intensity (TI)	− 1000	0	1700	2500

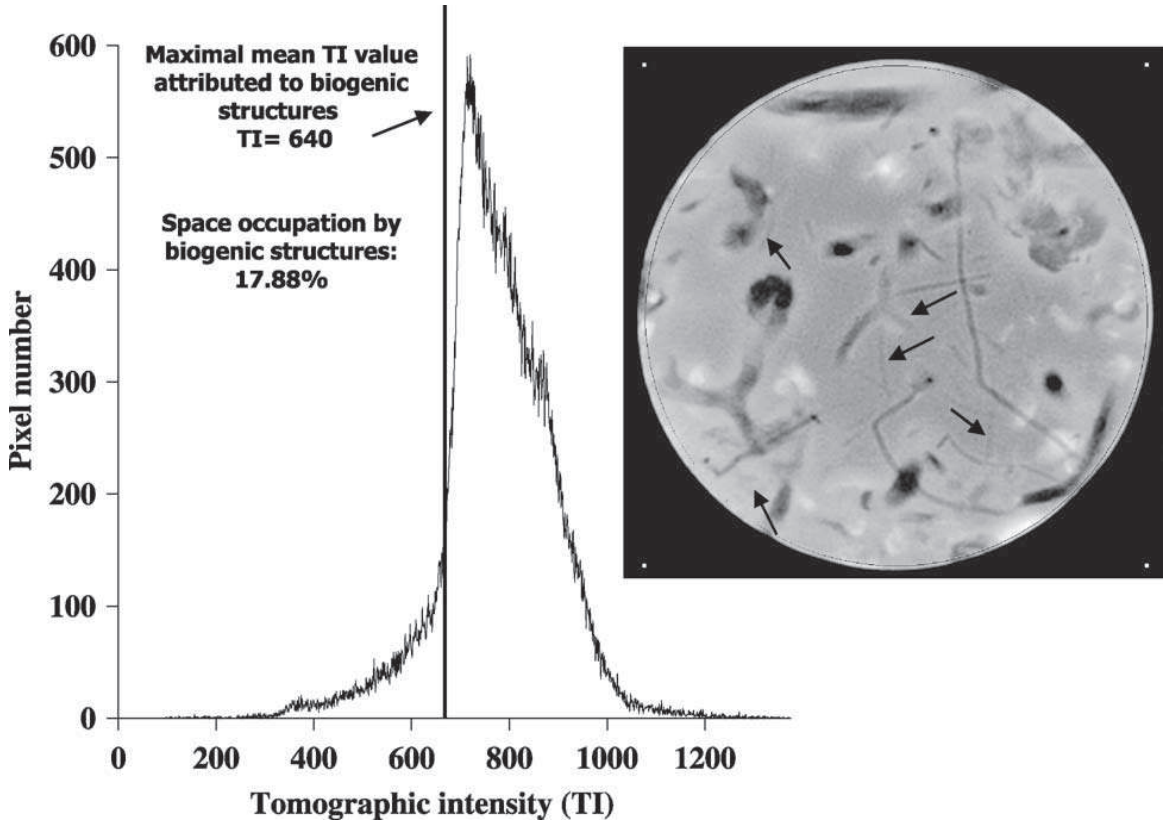

Fig. 3. Quantification of biogenic structures. For this transverse image (in the right-hand side), the Osiris software allowed us to determine the tomographic intensity of each pixel (in the left-hand side). In this slice, darker zones represented lower X-ray attenuation and lighter zones represented higher ones. The TI limit value between biogenic structure and sediment structure was represented by tomographic intensities of less visible biogenic structures. To define the TI associated with biogenic structures, a maximal intensity was calculated from five arbitrary points in five less visible biogenic structures. The average of these 25 points gave the maximal mean TI value attributed to biogenic structures in each transversal slice. All pixels with TI values lower than 640 were associated with biogenic structures.

structures in the transversal sections examined. All pixels with TI higher than this value were associated with sediment and all pixels with TI lower than this were associated with biogenic structures (Fig. 3). The ratio of biogenic structure pixels to total pixels gave the percentage of space occupied by biogenic structures. To determine an error estimate of the measured values, the sensitivity of the bioturbation limit value was calculated from five biogenic structures in each sediment slice. Considering the changes in mineralogy, grain size, and the general sediment compaction with depth, the density value assigned to biogenic structures was evaluated for each sediment slice. Finally, we obtained bioturbation profiles that indicated the percentage of space occupied by biogenic structures in the entire core.

2.5. Macrofauna data treatment

For each station, we studied the temporal changes of macrobenthic organism densities. For the ANOVA, the homogeneity of variance was tested on log transformed data. As time

is not an independent factor, data were then evaluated using repeated measures way ANOVA (Zar, 1998).

We determined the community composition at the species level between 1997 and 2000. Homogeneous groups of stations for these 4 years were singled out by cluster analysis (Clarke and Warwick, 1994) applied to a similarity matrix obtained by the coefficient of Sorensen and Bray–Curtis, which are, respectively, a qualitative coefficient based on the presence–absence of species and a quantitative coefficient based on their relative abundance (Sorensen, 1948; Bray and Curtis, 1957). Tables of dominant and subdominant species allowed us to interpret the Bray–Curtis index.

3. Results

3.1. Macrofauna densities

Macrobenthic organism densities for stations 2 and 13 sampled from 1997 to 2000 were used to study colonisation processes following the 1996 flood (Fig. 4). A previous study in September 1996 by Pelletier et al. (1999b) showed no macrobenthic organisms at station 2. The first organisms appeared in 1997. Organisms continued to colonise the sediment column until 1999 (3162 ind/m^2); benthic colonisation dynamics were suddenly disturbed between 1999 and 2000 (803 ind/m^2). An analysis of variance test highlighted a significant difference in the average abundance from 1997 to 2000 at station 2 ($F_{3,6}=20.77$; $p=0.0014$). At station 13, Pelletier et al. (1999b) showed that benthic fauna was less disturbed by the 1996 sedimentation event than fauna at station 2. The average abundance showed a slow and progressive colonisation from 1997 (181 ind/m^2) to 1998 (421 ind/m^2). A slight decrease in macrobenthic densities was observed until 2000 (242 ind/m^2). The ANOVA for station 13 did not indicate significant differences in abundances from 1997 to 2000 ($F_{3,6}=1.636$; $p=0.278$).

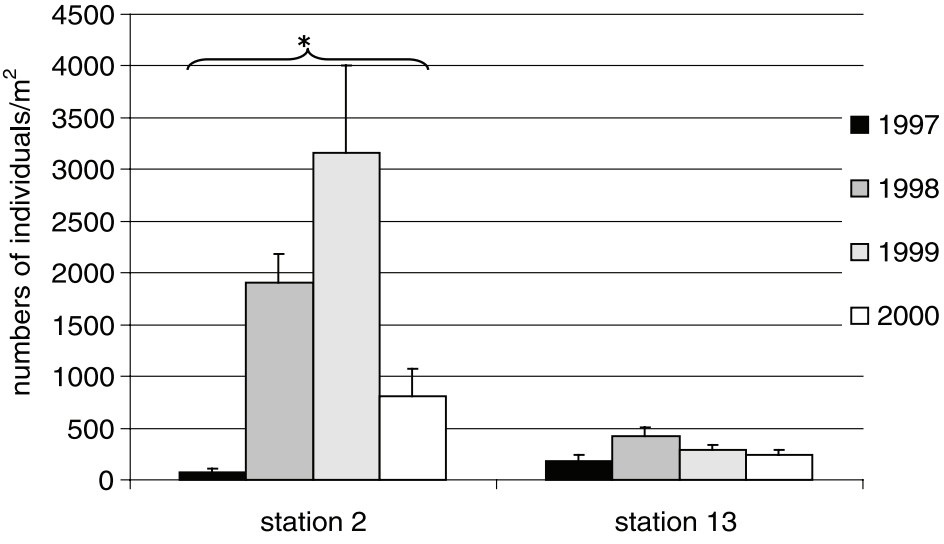

Fig. 4. Macrobenthic organism densities at stations 2 and 13 (Baie des Ha! Ha!, Saguenay Fjord) sampled from 1997 to 2000. *$p<0.05$ (ANOVA: $F_{3,6}=20.770$; $p=0.0014$).

3.2. Similarity coefficients

From a qualitative point of view, the dendrogram obtained with the Sorensen's index of similarity (Fig. 5) illustrated the high degree of affinity (50%) between the communities of the two stations from 1998 to 2000. Only station 2 in 1997 differed from other stations by a low affinity (17%). On the contrary, the dendrogram obtained with the Bray–Curtis index (Fig. 5) highlighted a marked separation between stations 2 and 13 (10%). The station 2 community in 1997 differed from the two station groups with a low affinity (8%). This result shows that species abundances for the two stations were different even though species compositions were very similar, as demonstrated by Sorensen's index. The differences obtained were essentially due to the dominance and subdominance of *Chaetozona setosa*, *Ampharate cf. arctica*, *Capitella capitata*, and *Cossura longocirata* at station 2, (Table 2) and *Macoma calcarea*, *Spionides* sp., *Lumbrineris fragilis*, *Scoloplos armiger*, and *Maldane sarsi* at station 13 (Table 3).

3.3. Scanographic longitudinal profiles and tomograms

Like the geological and geochemical survey conducted before 1999 (Pelletier et al., 1999b; de Montety et al., 2000; Savard, 2000; Crémer et al., 2002; Urgelès et al., 2002), the scanographic longitudinal profiles at station 2 in 1999 (Fig. 6) showed that the flood deposits were localised from 0 to 40 cm, representing the newly deposited 1996 flood sediments above old contaminated sediments, thus providing a natural capping layer. This tomogram (Fig. 6) indicated three main TI levels corresponding to three sedimentary facies for the sampled core. The high TI levels between 30 and 20 cm depth showed a succession

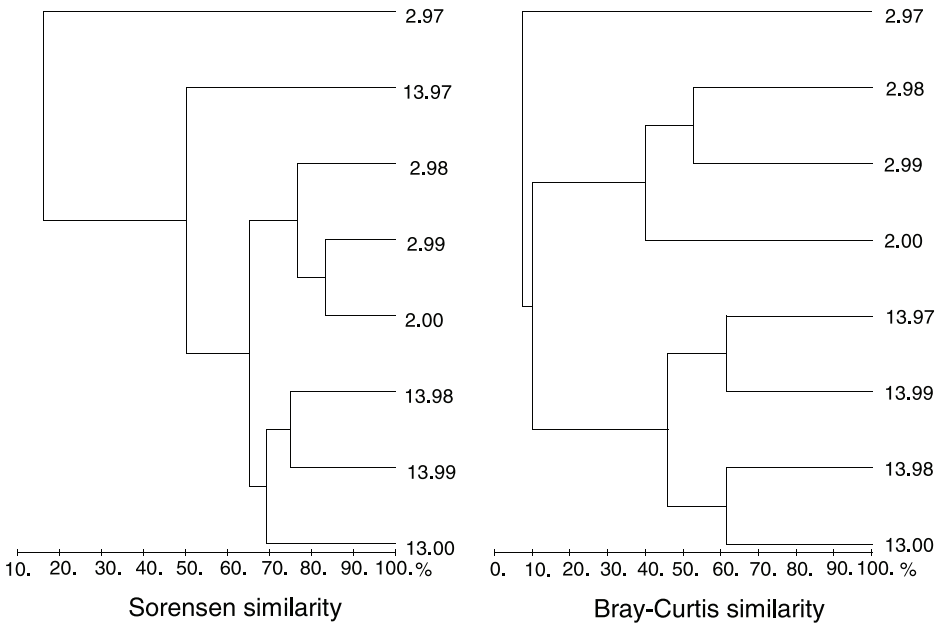

Fig. 5. Dendrogram of stations 2 and 13 of Baie des Ha! Ha! sampled over 4 years (1997–2000) using group-average clustering from Sorensen (1948) and Bray and Curtis (1957) similarities. Numbers on the figure indicate the stations (2, 13) and the year (1997–2000).

Table 2
Percentages of dominant and subdominant species, sampled with a Van Veen grab, at station 2 from 1997 to 2000

1997		1998		1999		2000	
Species	%	Species	%	Species	%	Species	%
Chaetozone setosa	92	*Chaetozone setosa*	34	*Chaetozone setosa*	61	*Ampharete cf. arctica*	35.74
Notomastus laticerus	4	*Ampharete cf. arctica*	29.4	*Cossura longocirrata*	18	*Chaetozone setosa*	28.52
Amphipoda Gammaridea	4	*Capitella capitata*	11.15	*Ampharete cf. arctica*	12	*Aglaophamus neotonus*	15.12
		Scoloplos armiger	8.9	*Capitella capitata*	2.27	*Cossura longocirrata*	12.37
		Arcidae suecica	5.15	*Lumbrineris fragilis*	1.94	*Terrebellides stroemi*	2.75
		Cossura longocirrata	3.76	*Scoloplos armiger*	1.35	*Scoloplos armiger*	1.37
		Lumbrineris fragilis	2.93			*Spionidae* sp.	1.37
		Arcidae nolani	2.37				

Table 3
Percentages of dominant and subdominant species, sampled with a Van Veen grab, at station 13 from 1997 to 2000

1997		1998		1999		2000	
Species	%	Species	%	Species	%	Species	%
Macoma calcarea	30.88	*Spionidae* sp.	41.3	*Lumbrineris fragilis*	35.3	*Spionidae* sp.	34.06
Lumbrineris fragilis	25	*Lumbrineris fragilis*	20.3	*Macoma calcarea*	28.23	*Lumbrineris fragilis*	20.88
Ampharete cf. arctica	17.62	*Ampharete cf. arctica*	9.1	*Scoloplos armiger*	10.6	*Macoma calcarea*	10.99
Notomastus laticerus	5.89	*Maldane sarsi*	9.1	*Chaetozone setosa*	9.41	*Maldane sarsi*	9.89
Maldane sarsi	5.89	*Nemerta*	4.2	*Tanaidacea*	4.7	*Scoloplos armiger*	5.49
Scoloplos armiger	5.89	*Chaetozone setosa*	3.5	*Ammotrypane aulogaster*	3.53	*Terrebellides stroemi*	5.49
Spionidae sp.	5.89	*Scoloplos armiger*	3.5	*Ampharete cf. arctica*	2.35	*Ampharete cf. arctica*	2.2
Amphipoda gammaridea	2.94	*Ammotrypane aulogaster*	2	*Maldane sarsi*	2.34	*Chaetozone setosa*	2.2
		Tanaidacea	2	*Capitella capitata*	1.18	*Harmothöe imbricata*	2.2
		Cossura longocirrata	1.4	*Aglaophamus neotonus*	1.18	*Molpodia oölitica*	2.2
		Aglaophamus neotonus	1.4	*Spionidae* sp.	1.18	*Aglaophamus neotonus*	2.2
		Harmothöe imbricata	1.4				

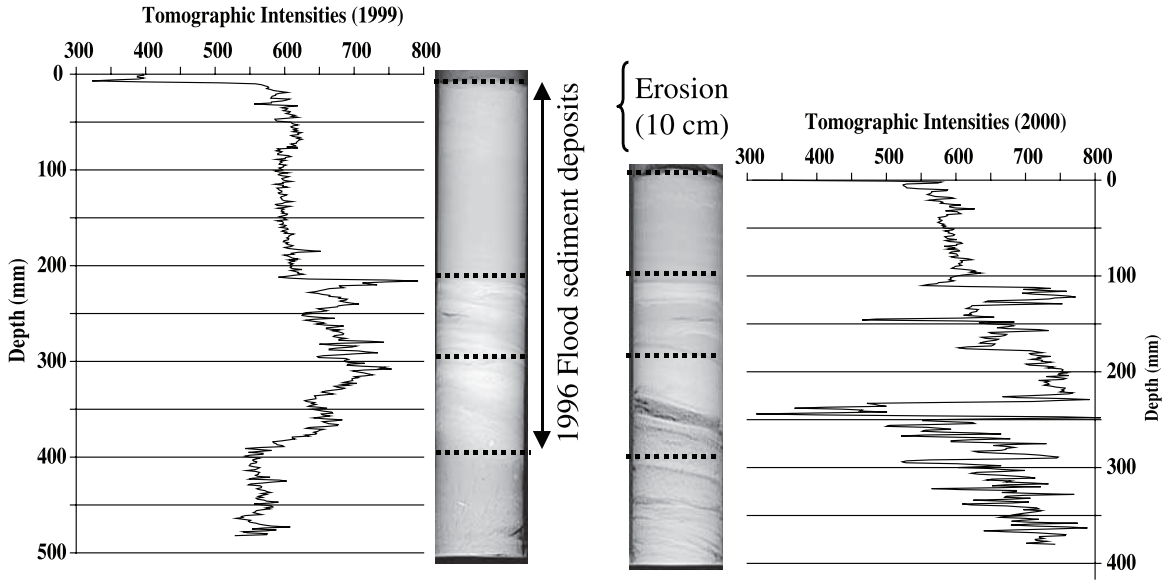

Fig. 6. Longitudinal scanographic profiles (tomogram) at station 2 in 1999 and 2000. Darker zones represented lower X-ray attenuation and lighter zones represented higher ones.

of laminated facies types, characteristic of silt and clay deposits (Crémer et al., 2002). Above 20 cm, the layer was essentially composed of muddy deposits (Crémer et al., 2002). The tomogram of station 2 in 2000 (Fig. 6) indicated that the thickness of the first level had been reduced to 10 cm. This is attributed to an erosional process that removed 10 cm of sediment between 1999 and 2000. The lower TI values at 25 cm (dark zones) were linked to deposits with high organic matter concentrations. The longitudinal scanographic profiles of station 13 in 1999 (Fig. 7) showed the 1996 flood deposits from 10 cm, as in observations from previous studies (Pelletier et al., 1999b; de Montety et al., 2000; Savard, 2000; Crémer et al., 2002; Urgelès et al., 2002). In 2000, scanographic longitudinal profiles of station 13 also indicated the 1996 interface from 10 cm (Fig. 7).

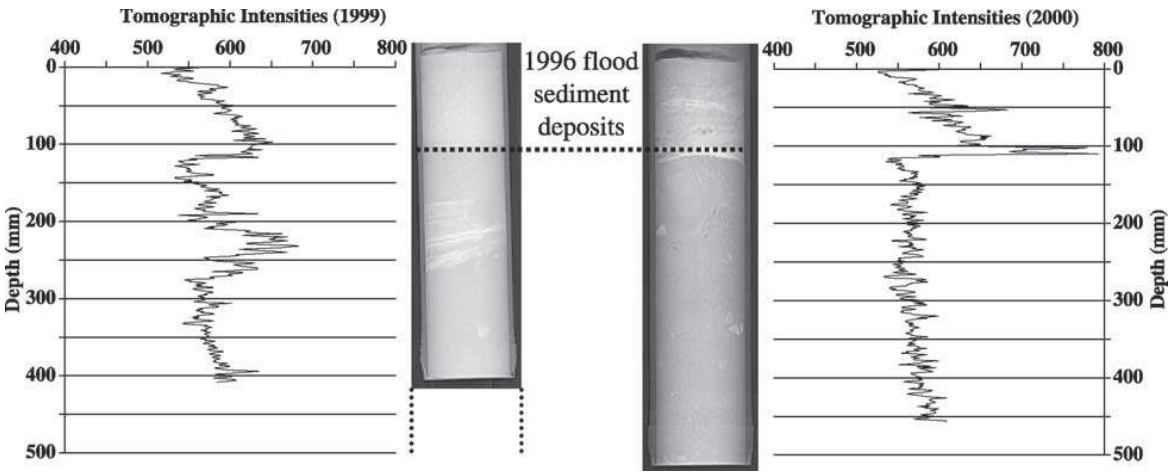

Fig. 7. Longitudinal scanographic profiles (tomogram) at station 13 in 1999 and 2000. Darker zones represented lower X-ray attenuation and lighter zones represented higher ones.

3.4. Bioturbation profiles

The quantification of biogenic structures was used to plot bioturbation profiles at stations 2 and 13 in 1999 and 2000 (Fig. 8). In 1999, data obtained for station 2 indicated a mean space occupation value of 37.2 ± 9% in the first 4 cm. This percentage decreased progressively between the surface and 20 cm in depth. After the erosional phase in 2000, the bioturbation profile had the same pattern, but with a mean percentage value of 21 ± 5% in the first 4 cm. Bioturbation profiles at station 13 also indicated a maximum percentage of space occupation above the first 4 cm for both 1999 (50.3 ± 9%) and 2000

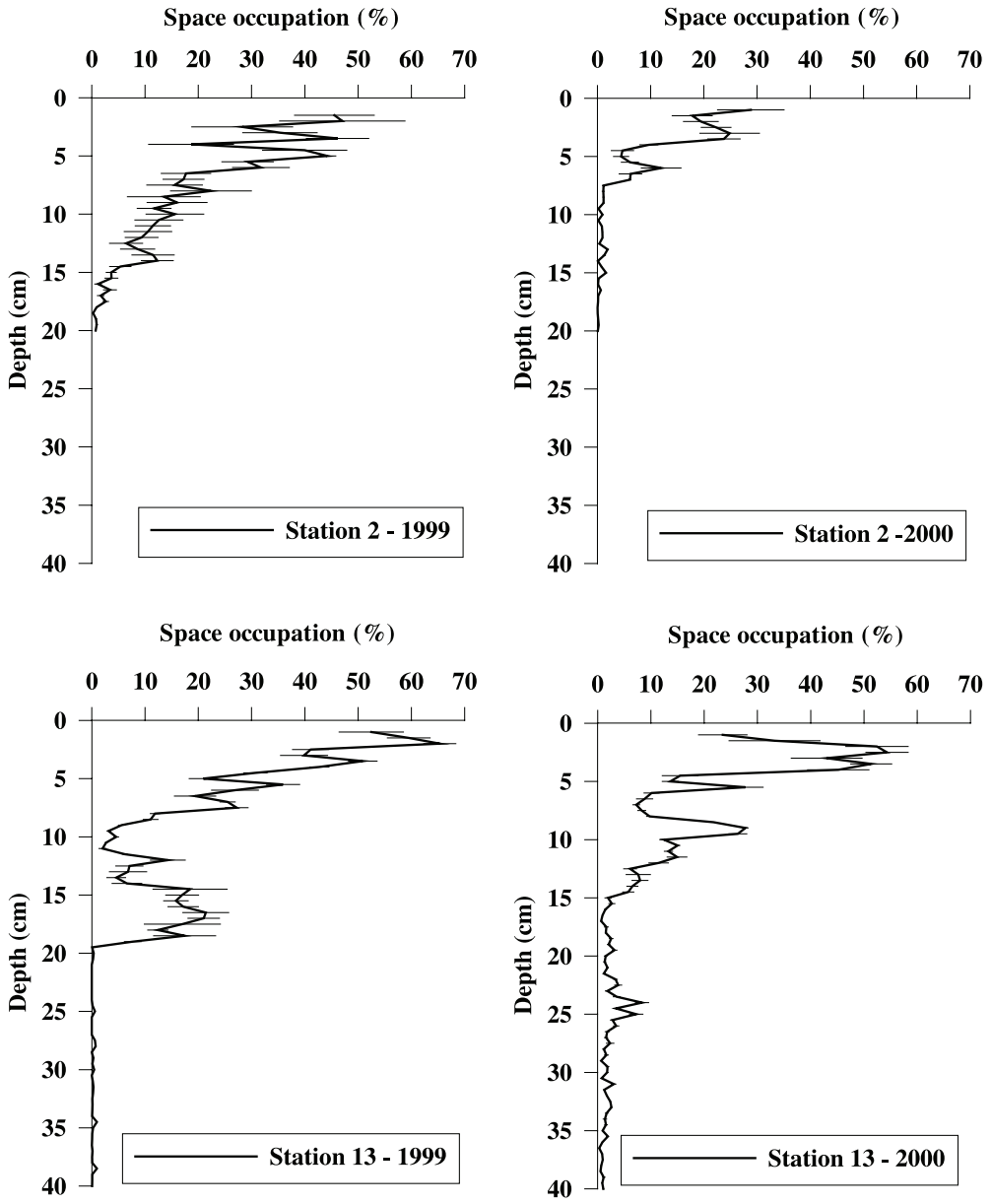

Fig. 8. Percentages of space occupied by biogenic structures (bioturbation profile) at stations 2 and 13 in 1999 and 2000. Error bars on the measured values indicate the sensitivity of the bioturbation limit value calculated from five biogenic structures in each sediment slice. Values are mean ± S.D. ($n = 5$).

(43.3 ± 10%). This percentage decreased progressively down to 40 cm in depth. Since 1996, no other sedimentary event has disturbed the benthic community dynamics at station 13.

4. Discussion

From the 1999 longitudinal scanographic profiles, we observed a series of sedimentary facies between 30 and 20 cm. Crémer et al. (2002), in a study of the upper 40 cm of sediments, revealed the presence of several facies types characteristic of a gravity deposit in the uppermost layer that were deposited during the 1996 flood. This layer rested on an erosional unconformity cut into the surface of the older deposits, themselves being gravity deposits. Those authors demonstrated that the succession of laminated facies between 30 and 20 cm characterised a series of sedimentary inputs during the 1996 flood. Dramatic changes in porosity, salinity, and organic carbon were also observed at this depth in sediment cores by Pelletier et al. (1999b). Michaud et al. (2001) showed that these massive sediment inputs during the 1996 flood disturbed the summit of the Ha!Ha! River delta's edge. In 2000, the deltaic slope had been destabilised with a seasonal flood (Michaud et al., 2001). Being located on this deltaic slope, station 2 had been submitted to erosion between 1999 and 2000. The specific nature of the facies in the prodeltaic and deltaic sequences is therefore dependent on sediment transport processes, re-deposition, and physical and/or biological reworking (Kuehl et al., 1995).

Early results of Pelletier et al. (1999b) concerning constant distributions of porosity, salinity, and organic carbon at station 13 indicated that this station was less disturbed by the massive sediment deposits of July 1996 than other stations located in the bay. The 1996 flood deposits were 10 cm thick in 1999 and 2000, indicating that no sedimentary event had disturbed station 13 between 1999 and 2000. Station 13 is located 9 km from the Ha!Ha! River delta at a depth of 125 m, which is far enough from the deltaic slope that landslides from the deltaic front had no direct influence on its sedimentation record (Michaud et al., 2001). The difference in the geographic locations between stations 2 and 13 with respect to the deltaic front causes an environmental gradient of physical disturbances on the macrobenthic distribution in the sediment column.

This different macrobenthic distribution between two stations was essentially due to the dominance and subdominance of *C. setosa*, *A. cf. arctica*, *C. capitata*, and *C. longocirata* at station 2 (Table 2) and *M. calcarea*, *Spionides* sp., *L. fragilis*, *S. armiger*, and *M. sarsi* at station 13 (Table 3). Table 2 showed, moreover, that the number of deep dwellers at station 2 (*Aglaophamus neotenus* and *Terrebellides stroemi*) were less affected by the erosion than the number of surface/shallow dwellers (*C. setosa* and *C. longocirata*). The reduction in the population density at station 2 might be directly related to the surface layer erosion.

An extended period of seabed stability at station 13 enabled organisms to occupy a large space in surface sediment layer in 1999 and down to 40 cm depth in 2000. Biogenic structure occupation at station 13 was attributed to both actively used and relict burrows made by benthic organisms between 1996 and 2000 and to old tracks made before the flood. To follow the dynamic evolution of biogenic structures between 1999 and 2000,

bioturbation profiles were plotted together in Fig. 9. The similar space occupation by biogenic structures in the sediment column between 1999 and 2000 (Fig. 9) indicated a steady state between the destruction and preservation of biogenic structures in an area submitted to a constant sedimentation rate since 1996 (Michaud et al., 2001). Berger et al. (1979) and Kuehl et al. (1995) also emphasised the importance of production and destruction rates of biogenic structures and the sedimentation rate for the preservation of burrows and potentially reactive components.

During the erosional period between 1999 and 2000, benthic organisms at station 2 were lost with sedimentary material (from 0 to 10 cm) and organic matter. The new sediment–water interface, just after the erosion, corresponded to the layer of 1999 from 10 cm depth (Fig. 9), which included the biogenic structures and organic components present before the erosion. This new "eroded layer" (Fig. 9) was less occupied by biogenic structures just after the erosion (black curve). This curve was plotted with the space occupation of 2000 (Fig. 9). Occupation percentages obtained in 2000 (grey curve) were attributed to new structures created between the erosion and sampling time and to old tracks in the 1999 layer between 10 and 20 cm. The differences between the two profiles correspond to the minimum percentage of new biogenic structures appearing after the erosional event. The results suggest that the bioturbation profiles obtained in 1999 represented the colonisation state in the sediment column over 3 years (mean occupation percentage between 0 and 20 cm depth: 15.89%). Bioturbation profiles obtained in 2000 represented the colonisation state in the sediment column 1 year after the erosional event

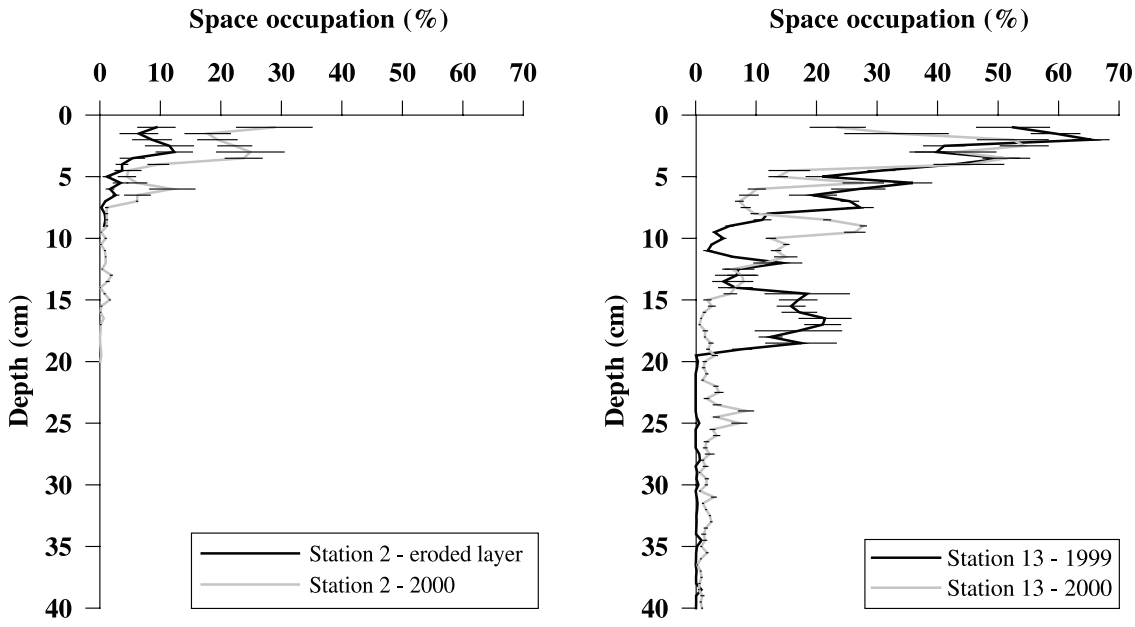

Fig. 9. Space occupation percentages of biogenic structures (bioturbation profile) at station 2 in the eroded layer which included biogenic structures of the deeper layer from 10 cm in 1999 (black curve), and in 2000 (sediment column 1 year after the erosional event). Space occupation percentages of biogenic structures (bioturbation profile) at station 13 in 1999 and 2000. Error bars on the measured values indicate the sensitivity of the bioturbation limit value calculated from five biogenic structures in each sediment slice. Values are mean ± S.D. ($n = 5$).

(mean occupation percentage between 0 and 20 cm depth: 5.2%). This colonisation state is related to buried organisms that resisted the erosional event, but could also be the result of the activity of organisms that colonised the sediment column between the erosion event and the sampling time.

After the erosional event, the period of seabed stability enabled benthic animals to modify their new biotope by bioturbation processes (Kuehl et al., 1995; Aller and Stupakoff, 1996). The erosional event at station 2 was followed by rapid benthic colonisation activities due to high rates of net sedimentation with high rates of terrestrially derived organic material characterising deltaic environments (Pearson and Rosenberg, 1978; Kuehl et al., 1995; Aller, 1998). The introduction of new reactive organic material could promote a mechanical stimulation of microbial assemblages and activities (Zajac and Whitlatch, 1982; Pearson and Rosenberg, 1987; Aller, 1989). The new physical and chemical properties of the sediment (Mucci et al., 2000) and the low competition between species are also factors favouring larval recruitment (Pearson and Rosenberg, 1978; Prena et al., 1997). Intense and new massive biological sediment reworking in deeper layers should have allowed an efficient re-mineralisation and re-oxidation of organic matter (Canfield, 1994; Kristensen et al., 1995; Hulthe and Hall, 1998).

The erosion of surficial sediments at station 2 caused a succession in the formation of biogenic structures that was characterised for the first time by CAT-Scan. This preliminary study used CAT-Scan with no replication and therefore takes no account of natural variability in benthic ecology. However, these early results, in accordance with geological studies (Crémer et al., 2002), suggest the technique should be investigated further and applied more widely and with proper replication to determine its usefulness. More precise than longitudinal X-ray analysis (Aller and Aller, 1986; Aller, 1989; Kuehl et al., 1995; Aller and Stupakoff, 1996; Gérino et al., 1999), the CAT-Scan is a nondestructive, rapid, and precise method to examine transverse sections where biogenic structures are visualised. The CAT-Scan is a powerful tool to study the dynamics of benthic communities by quantifying current and unused biogenic structures according to physical sediment disturbances. As colonisation processes are closely linked with stability of the sediment column, such a precise quantification of biogenic structures enables the assessment of potential biogeochemical functioning in the sediment column.

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