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THE EFFICIENCY OF A CATASTROPHIC CAPPING LAYER DEPOSITED IN THE SAGUENAY FJORD DURING THE FLOOD OF 1996, QUEBEC.

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ABSTRACT
In July 1996, an important flood took place in the Saguenay region, in Quebec. This disaster was marked by the catastrophic swelling of some tributary rivers of the Saguenay Fjord, which carried and deposited about 20 million tons of sediment in the upstream section of the fjord. This event not only had bad consequences because the new sediments have recovered the underlying contaminated sediments with a clean layer of sediment over a large surface. Taking advantage of this opportunity, a group of scientists and engineers has worked on several aspects of this flood layer to evaluate its performance as a geological barrier for contaminants from geological, geotechnical, hydraulic, geochemical and biological point of view. This paper presents some results about the performance and integrity of the capping layer. Up to now, the layer is effective to isolate the contaminants, but in long- term, it seems that bioturbation, erosional and slope instability related processes are the most important factors that might affect the integrity of the flood layer.

RÉSUMÉ
En juillet 1996 d'importantes précipitations se sont produites dans la région amont du fjord du Saguenay. Ce désastre a été marqué par des crues catastrophiques de quelques rivières tributaires du fjord du Saguenay, lesquelles ont transporté autour de 20 millions de tonnes de sédiments dans la portion amont du fjord. Cet événement n'a pas eu que des conséquences dramatiques puisque les nouveaux sédiments ont recouvert les sédiments contaminés préexistants d'une couche de sédiments propres sur une vaste surface. En voulant profiter de cette opportunité, une étude multidisciplinaire a été entreprise pour évaluer l'intégrité de la couche comme barrière géologique d'un point de vue géologique, géotechnique, hydraulique, géochimique et biologique. Cet article présente une description du projet et quelques résultats sur la performance et l'intégrité de la couche de recouvrement. Jusqu'à maintenant, la couche est efficace pour isoler les contaminants, mais à plus long terme, il semble que la bioturbation, l'érosion et la stabilité des pentes sont les facteurs qui affectent le plus l'intégrité de la couche.

1. INTRODUCTION

In July 1996, a catastrophic flood took place in the Saguenay region (Fig. 1). The major tributary rivers of the upstream portion of the Saguenay Fjord have eroded and transported more than 20 millions tons of sediments, which were deposited on the bottom of the fjord. This new sediment deposit covered the contaminated sediments present in this portion of the fjord with a clean layer of sediment. The underlying sediments are principally polluted with mercury and polyaromatic hydrocarbons (Pelletier and Canuel 1988). The mean thickness of this new layer varies from 10 to 60 cm, but reaches up to 7 m close to the main river mouths.

The 1996 event created a major perturbation in the various processes involved at the sediment-water interface. During the first investigation, barely 3 weeks after the flood, the benthic community was almost destroyed. The biodiversity decreased from 40 to 4 species and the density of the most abundant species, nematodes, was reduced by ten-fold (Pelletier *et al.* 1999). Also, the new deposit has modified the geochemical steady state at the sediment-water interface causing the upward migration of the redox limit and the remobilization of some metals (Mucci *et al*. 2000a).

This project offers the opportunity for sediment capping technology because of the large surface of sediment covered by the flood material and also because the site, which is a simple sedimentation environment, is well known by the group of researchers.

The objectives of the research project are: 1) to determine whether the mechanical and chemical stability/behavior of the flood layer will allow final burial of the formerly contaminated sediments of the Saguenay Fjord, and 2) to develop predictive models of environmental recovery rates, and of the mechanism involved, which will be based on the monitoring of the geochemical and mechanical evolution of the flood layer and on the re-establishment of the benthic life. Thus, this paper presents some results that indicate the effectiveness of the new layer as a geological barrier to isolate the underlying contaminants.

2. CAPPING LAYER OVERVIEW

In situ subaqueous capping of contaminated sediments is an effective method to protect the aquatic environment from the toxicity of many pollutants. This remedial method has been successfully used in Canada to prevent the upward

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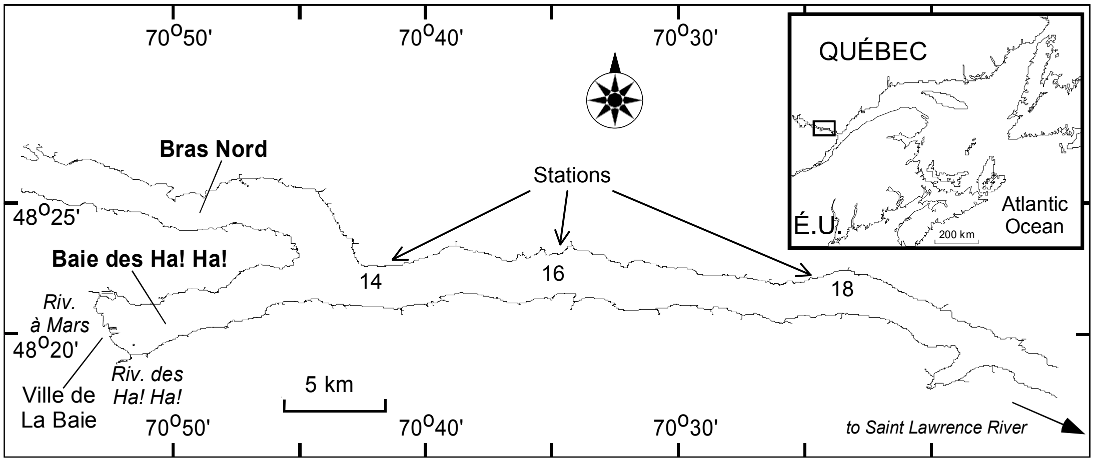

Figure 1. Localization map and studied stations.

migration of organic contaminants, *e.g.* in Hamilton Harbor (Zeman and Patterson 1997).

The main purpose of a capping layer is to isolate physically and chemically the contaminants present in the sediments and to prevent their resuspension and transport (Palermo *et al.* 1998). The addition of a clean layer over contaminated sediments prevents benthic organisms to be in contact with contaminants and reduces the flux of dissolved contaminants towards the water column by promoting a better retention provided by addition of new adsorption sites. In other words, it considerably reduces the contaminant mobility.

Some elements must be considered for the design of capping layer. Palermo (1991) and the USEPA (1994) suggest paying attention to the following points: (1) characterization of the contaminated sediments, (2) selection and characterization of the site, (3) selection and characterization of the capping material, (4) determination of the capping thickness, (5) selection of equipment and placing method, and (6) planning of the monitoring program.

In our case under consideration, because of the natural generation of the capping layer, not all the previous points above should be considered. Then, it is important to note here that, we had no control on selection of the site, capping material, equipment and placing method, nor the capping thickness. Therefore, our project focuses on the point 6, the monitoring program, which, according to Palermo (1991), consists to insure the adequate placement of the capping layer and most of all, the long-term integrity of the layer.

3. STRATEGY AND METHODOLOGY

The project, started in 1998, extends over five years to ensure that the various index or changes could be monitored. Each summer, series of cruises onboard scientific ships enabled sediment sampling and geophysical and sonar surveys are carried out to achieve the above mentioned objectives. The review of the strategy and methodology will be made by considering the following aspects: mechanics, geochemistry and biology.

3.1 Mechanical aspects

For the purposes of the project, the first step was to evaluate the extent of the flood layer in terms of geometry, morphology, and thickness. To achieve these, a series geophysical and multibeam sonar surveys were carried out and compared with pre-flood surveys. These surveys were validated by an extensive sampling program using box, Lehigh and piston cores. Also, using sequential multibeam back scattering data, the evolution of the capping layer was monitored in terms of consolidation rate trough water content, surface roughness and biological colonization. Here also, the study was supported by a comprehensive surface sampling program (more than 200 samples).

Basic geotechnical properties (grain size distribution, Atterberg limits, shear strength) were determined. The results were used to develop a bioturbation/consolidation model but also in support of the stability and erodability analyses. Stability analysis are related to geophysical and a GIS data base. Stability and erodability studies are actually running, thus they won't be tackled in this paper.

3.2 Geochemical aspects

When a layer of sediment is placed upon existing sediments, many substances can be remobilized as a result of diagenetic process that tends to reach a new steady state. To explain this phenomenon, a geochemical reactor has been developed. It represents the diagenetic evolution of the sediments as well as the nature and the flux of the contaminants that would be remobilized trough the capping layer. To do so, numbers of trace metals, such as Fe, Mn, Hg and As, and organic contaminants, *i.e.* PAH and CH_3Hg^+ were monitored both in the sediments and porewaters from box core samples every year at 7 major stations.

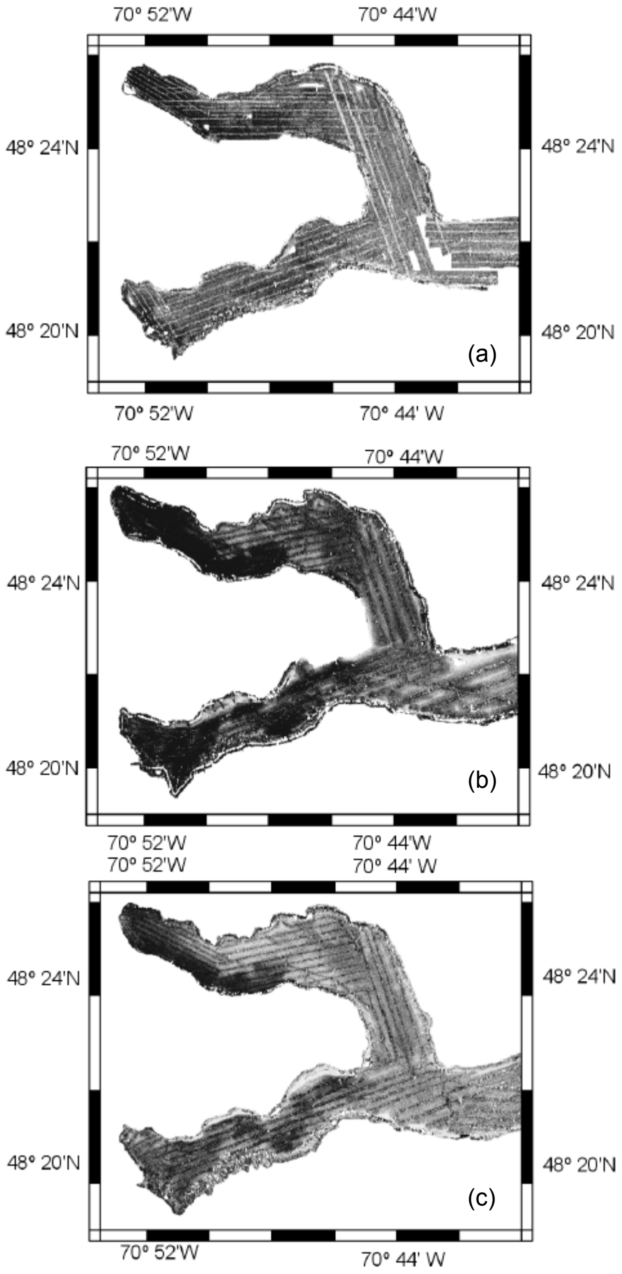

Figure 2. Temporal changes of the backscatter over three multibeam sonar surveys in (a) 1993, (b) 1997 and (c) 1999 (from Schmitt *et al.* 2000).

A laboratory investigation has been conducted under controlled environments, which simulated the *in situ* oxido-reduction conditions, to determine how the contaminants are mobilized or retained, in particular, heavy metals and their affinities for the solid matrix constituents. This will assist in the evaluation of the potential for mobility. Zn, Cu and Pb have been studied during this project. However, the results are not available now and they won't be treated in this paper, but they will provide the various inputs to the physico-chemical transport model.

3.3 Biological aspects

The benthic life has been strongly affected by the fast accumulation of sediments during the flood. As mentioned earlier, the density of species has been reduced or even many species disappeared. The recolonisation in terms of abundance and diversity of the different species was evaluated at selected sites. The main goals were (1) to quantify the effect of the capping on the benthic and planktonic populations, (2) the restoration of the biological activity in sediment and the mechanical mixing rates and (3) to provide an index of environmental recovery.

Three scales of benthos life were investigated: microfauna (foraminifera), meiofauna (organisms with dimension between 0.63μm and 1mm, *e.g.* nematodes), and macrofauna (dimension > 1mm, *e.g.* worms). Only meiofauna and macrofauna will be considered here.

4. RESULTS

4.1 Mechanical aspects

4.1.1 Morphology and geometry of the flood layer

The extent of the layer was established from multibeam sonar surveys (SMIRAD EM1000) and box core sampling. As shown on Figure 2, there is a difference in the reflectivity (backscatter) of sediments before (2*a*) and after (2*b*) the flood. The darker zones in Figure 2*b* correspond to the limits of the new layer of sediments that seems to end just downstream of the confluence of the Baie des Ha! Ha! and the Bras Nord (Schmitt *et al*. 2000). The evolution of the layer in 1999 (2*c*), will be discussed in the next section. Numbers of box core samples were taken in this area. They revealed a thickness varying from 10 to 60 cm in most of the sector, but generally decreasing in a downstream direction (Maurice *et al*. 2000). Close to the river mouths of the Baie des Ha! Ha!, the accumulation of sediment can reach 7 m (see profiles on Fig. 3). Also, this last figure shows the surface morphology of the sediments on the delta of the Rivière des Ha! Ha!, where the maximum accumulation of sediments was registered.

4.1.2 Evolution of the sediment characteristics

The works of Schmitt *et al.* (2000) have revealed that it is possible to follow the temporal evolution of the sediment properties (particularly water content, grain size and density) after their placement. On figure 2, the darker zones correspond to intense sedimentation and could be due to high water contents in the newly accumulated sediments, which causes low reflectivity. As the water content decrease with time, as well as the thickness and density due to consolidation process, the reflectivity increases showing more light zones in 1999 (2*c*). However, it seems that the surface roughness and the density of the benthic organisms also contribute to increase the reflectivity. Thus, the multibeam sonar could be an interesting tool to evaluate the recolonisation and the evolution of the sediment properties after the deposition of a capping layer.

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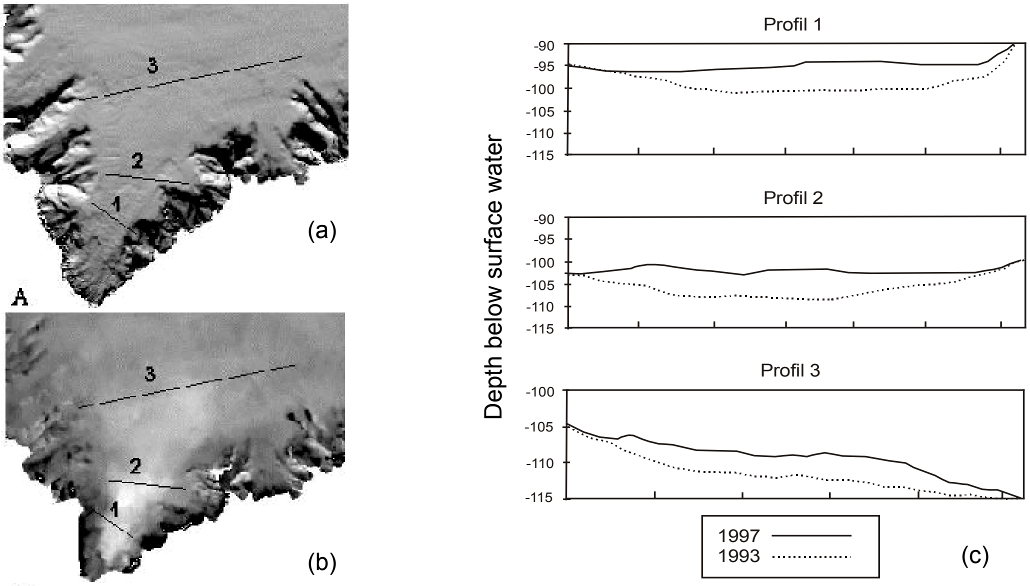


Figure 3. Detailed view of the area close to the Rivière des Ha!Ha! mouth acquired with SIMRAD EM1000 multibeam sonar; (a) bathymetry (1997), (b) DTM difference (white areas correspond to the zones of sediment accumulation between 1993 and 1997), (c) three profiles showing the amount of deposition (from Kammerer *et al.* 1998).

Other sonar surveys are planned for the summer of 2001 to confirm the influence of sediment characteristics on the evolution of the backscatter.

4.1.3 Geotechnical properties and consolidation model

The flood layer is a turbidite usually characterized by a thin sand layer at the bottom. The grain size distribution varies from sand to clay. Near the river mouths, the sediments are coarser and are mainly constituted of sand and gravel, which means that the sampling method, by gravity, is ineffective in that portion of the fjord. Compared to sediments existing before the flood, they are lighter, contain less organic matter, have higher water content, a weaker consistence and a lower placticity index (Maurice *et al.* 2000). In the Bras Nord, the new layer is harder to identify because bioturbation is more important and has quickly erased the signature of the turbidite through mixing of sediments. The consolidation of the new layer was completed after 3 months, meaning that the excess pore pressure was quickly dissipated.

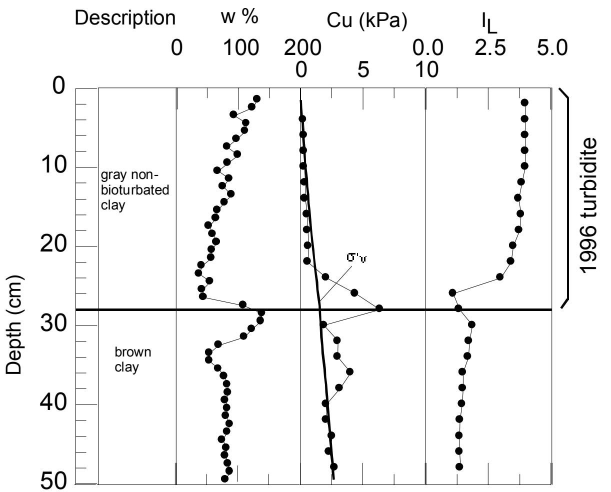
In their works, Maurice *et al*. (2000) have noted that the bioturbation influences the consolidation behavior of turbidite (Fig. 4). In fact, the bioturbation contributes to increase the shear resistance by reducing the liquidity index (I_L). Soon after depostion, I_L is at about 4, but rapidly decreases to a value near 2 once the bioturbation has been well established within the flood layer. This cause the water content to increase with depth as the organism activity decreases with depth (Fig. 4*b*). They mention that if the thickness of the layer is greater than the limit depth of activity for the organisms (40 cm for the Saguenay Fjord), a high water content and a weak resistance would persist below this limit.

To explain the consolidation behavior related to bioturbation, Maurice *et al*. (2000) have proposed a model as shown on Figure 5. The virgin consolidation curve was obtained from reconstituted samples using large sedimentation-consolidation cells (Perret *et al*. 1995). This figure illustrates the consolidation behavior of the turbidite affected by bioturbation. Just after the flood (at t_0), when recolonisation was almost inexistant, I_L values, stabilized around 4 and joined the virgin curve as the depth increases. As the time passes ($t_1 \rightarrow t_4$), the bioturbation increases, and the sediment density, under low stress conditions (*i.e.* near the surface), decreases progressively. Thus, the density stabilized at a corresponding $I_L=2$ that seems the lowest value that can be reached by bioturbation for this region. The depth at which curves t_1 to t_4 raise, represents the limit depth for bioturbation at the corresponding time. For example, at time t_2, the organisms activity has reach a depth of about 20 cm. Below this point, I_L increases to join the virgin curve. This translates on a geotechnical profile by a decreasing resistance and increasing water content below the bioturbation depth. What we usually observe for a non-bioturbated sediment is a constant increasing resistance and decreasing water content with depth (Fig. 4).

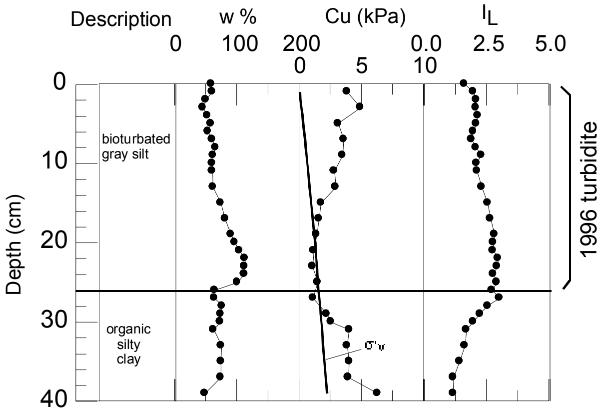
4.2 Geochemical aspects

4.2.1 Geochemical tracers

A monitoring program following a capping layer placement must include the selection of good tracers that provide information on the position of the interface between the contaminated sediments and the capping layer, or on the mixing of the different layers. The material composing the capping layer in the Saguenay Fjord has a terrestrial origin (St-Onge and Hillaire-Marcel 2000). Then, it has a different



(a) non-bioturbated



(b) bioturbated

Figure 4. Geotechnical profiles of the 1996 turbidite; (a) non-bioturbated sample taken in the Baie des Ha! Ha! in 1997, and (b) bioturbated sample taken in the Bras Nord in 1998 (after Maurice *et al*. 2000).

geochemical signature than the indigenous sediment. Deflandre *et al*. (2000) and Mucci *et al*. (2000a) have measured a distinct variation of organic and inorganic carbon content in the 1996 layer compared to pre-flood sediments (Figure 6). They noted that the organic carbon is less abundant in the capping layer than in the indigenous sediments. In contrary, the inorganic carbon, which is almost undetectable in the contaminated sediments, is very high in the flood layer. The inorganic carbon is mostly composed of calcareous materials contained in the eroded material. According to Mucci *et al*. (2000b), the anoxic condition prevailing in the Saguenay Fjord sediments, will preserve the carbonate, meaning that the inorganic carbon content will be a useful tracer to identify the capping layer in the future monitoring works.

4.2.2 Geochemical reactor

The geochemical steady-state conditions encountered in the Saguenay Fjord sediments are characterized by an accumulation of reactive manganese and iron in the oxic layer that is located in the first 5 mm of sediments. The deposition of a new layer on top of existing sediments disturbs the steady-state of diagenetic process. According to Mucci *et al.* (2000a), only three weeks after the flood, the oxido-reduction boundary has rapidly migrated through the new layer up to the first millimeters of the new water-sediment interface. The migration of the redox limit has affected the remobilization of some metals while others have been trapped at the old water-sediment interface. A geochemical reactor was developed to explain the fate of trace metals after the deposition of an inorganic layer such as capping layer (Mucci and Edenborn 1992; Mucci *et al*. 2000).

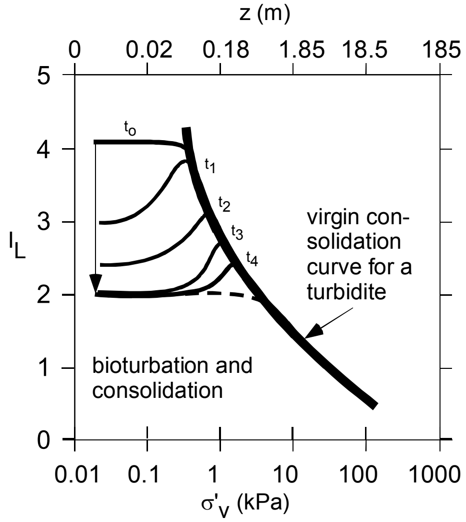


Figure 5. Evolution of the flood layer with time under the influence of bioturbation (from Maurice *et al*. 2000).

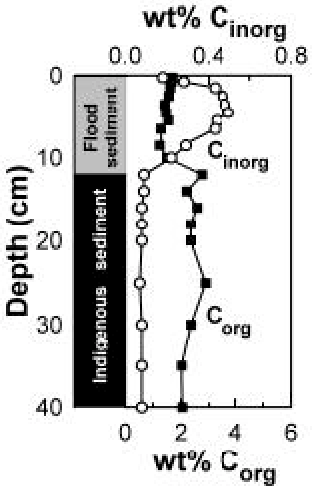


Figure 6. Profiles of organic and inorganic carbon content in sediment (from Deflandre *et al*. 2000).

The Figure 7 presents the schematic remobilization of Fe and Mn after the flood material deposition (Mucci *et al*. 2000a). The steady-state conditions prevailing before the flood are illustrated in Fig. 7*a* where the Fe^{+2} and Mn^{+2} ions precipitate in the oxidized layer as MnO_x and $Fe(OH)_3$.

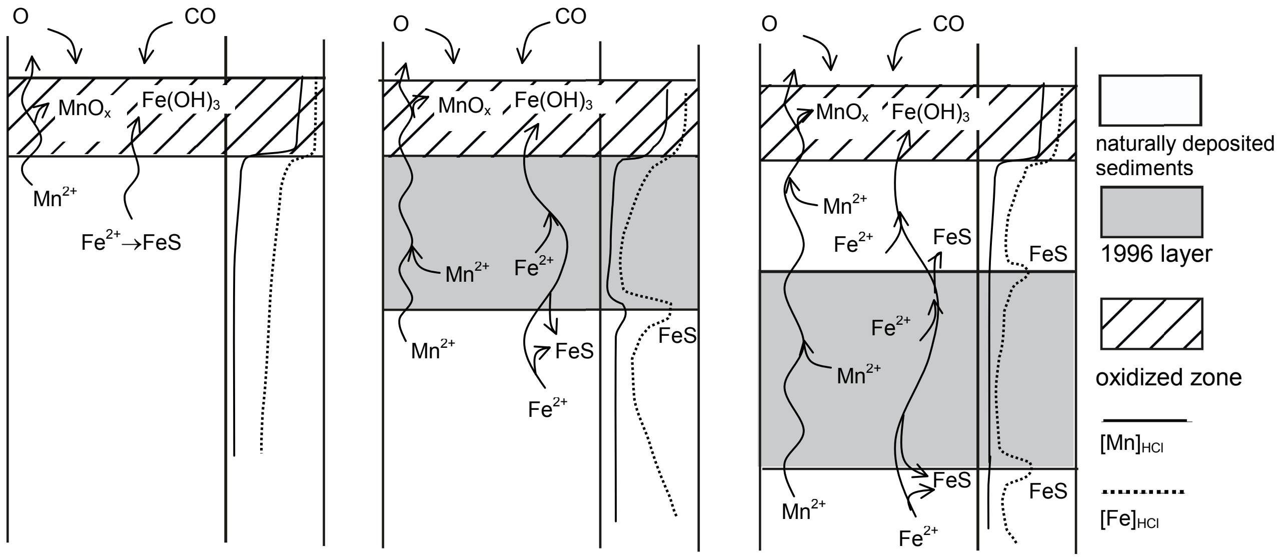


Figure 7. Schematic representation of the remobilization of Fe and Mn and the migration of the oxidation front following the deposition of the flood layer in 1996 (Mucci *et al*. 2000a).

Immediately after the deposition of the catastrophic layer, the redox front begins to move up to few millimeters upward from the new water-sediment interface (Fig. 7*b*). As a consequence, the bottom of the flood layer, below the redox front, becomes suboxic or anoxic, leading to the leaching of reducible Fe and Mn that were accumulated at the bottom of the flood layer. Then, the reduce Mn and part of Fe migrate to the new oxidic zone where they re-precipitate following oxidation. Part of the Fe is trapped as mono-sulfides (FeS), due to the rapid onset of sulfidic conditions. As the normal sedimentation continues above the flood layer (Fig. 7*c*), the oxidized zone is re-established in the indigenous sediments and part of the reduced Fe precipitate as FeS at the top of the catastrophic layer while the Fe that remains and the Mn continues to migrate to the new water-sediment interface, where it accumulates. Then, the steady-state conditions are re-established.

4.2.3 Contaminant behavior

The previous section explained how the diagenetic conditions were perturbed by the mass deposition of the catastrophic layer. Many contaminants present in the pre-flood sediments were monitored to evaluate their transport potential throughout the capping layer. However, only few of them are discussed hereafter, which are As and Hg. Preliminary results indicates that As is trapped by co-precipitation with the iron sulfides (Mucci *et al*. 2000a) at the old water-sediment interface. Total mercury and mono-methylated mercury (CH_3Hg) in the solid sediments are also trapped at the original water-sediment interface. However, little accumulation of CH_3Hg in the solid sediments and porewaters was registered in samples collected in 1999 within the first 5 cm of the surface of the flood layer. This peak is though to be associated with the normal sedimentation regime and mixed with underlying sediments by bioturbation down to 5 cm (Mucci *et al*. 2000a). De Montety *et al*. (2000) mentioned that the benthic activity is maximum within the first 5 cm, which supports the assumption of an important mixing of the sediments near the new water-sediment interface.

4.3 Biological aspects

4.3.1 Evolution of benthic community

The placement of a capping layer affects benthic life. The organisms are buried under the layer and their habitat is modified, *e.g.* by placement of a sand layer over clayey sediments. The important quantity of sediment transported and deposited in the upstream portion of the Saguenay Fjord was a disaster for the benthic communities. In September 1996, two months after the flood, Pelletier *et al*. (1999) reported that in the Baie des Ha! HA! (see Stations 1 to 13 in Fig. 9), the meio-fauna was reduced in population by more than 97% (Fig. 8). One of the pre-flood species (nauplii) was absent in all the stations (see Stations in Figs. 1 and 9). Also, two families of meio-fauna (kinorhynches and ostracodes) were found in only one station (St. 18) located downstream of the area covered by the flood deposit. They same authors have also registered a dramatic reduction of the macro-fauna. In two of the stations monitored two months after the flood (St. 2 and 3 in Figs. 9), the macro-benthic organisms were totally absent. Event if the population is abundant in most of the investigated stations, they are less abundant than those reported by Bossé *et al*. (1996) before the flood.

Although not compiled in Figure 10, subsequent investigations, after 1997, the global benthic population has increased in all the affected sector of the Saguenay Fjord, but has not reached the pre-flood value.

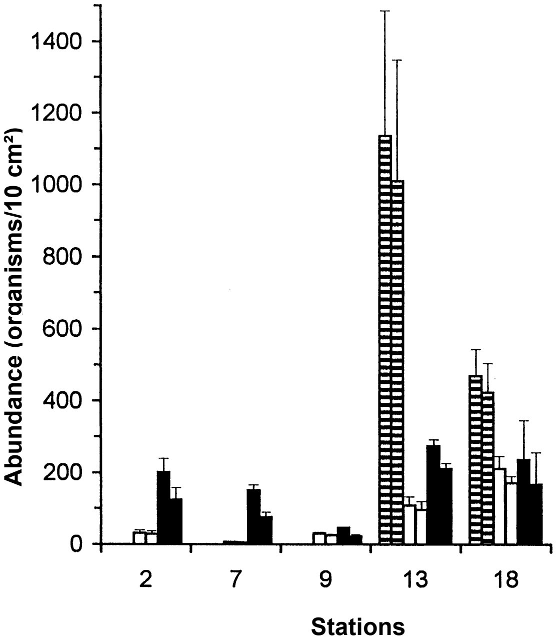


Figure 8. Abundance of the meio-fauna. For each pair of bar, the left one is the mean density of the meio-fauna and the right is the abundance of nematodes per unit surface (10 cm²). Striped bars = May 1996 (*e.g.* before the flood); white bars = September 1996 (2 months after the flood); black bars = August 1997 (from Pelletier *et al*. 1999).

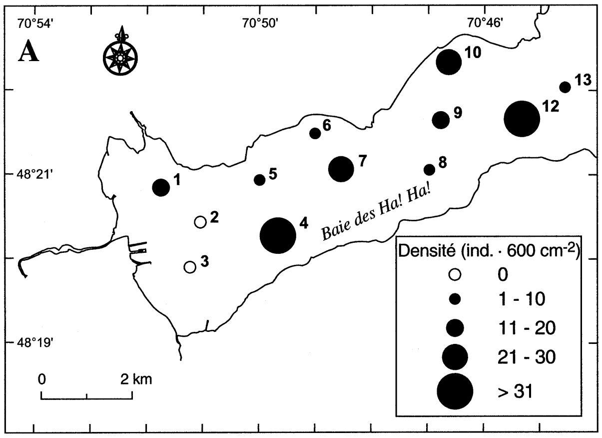


Figure 9. Spatial distribution of the macro-benthic organisms (from Pelletier *et al*. 1999)

4.3.2 Biological tracers

Some species are recognized to be pioneer species, meaning that they are the first to recolonized a given environment after a catastrophic event, like a flood or an antropogenic activity, such as dredging or capping. In capping projects, we need to identify one or more species, which are indicators of the degree of contamination of an environment. The *Macoma calcarea*, a mollusk, has considerably and rapidly increased during the years following the flood event (Pelletier *et al*. 1999). In addition, this species is described as a good indicator of the contamination and also as a recolonization specie of anoxic environment (Peason and Rosenberg 1978). Therefore, it was selected to monitor the recovery capacity of the benthic ecosystem of the Saguenay Fjord.

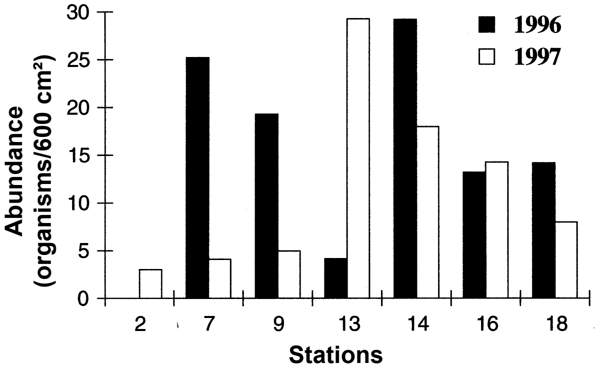


Figure 10. Abundance of macro-benthic organisms at different station after the flood in 1996 and 1997 (from Pelletier *et al*. 1999).

5. GLOBAL PERFORMANCE AND INTEGRITY OF THE CAPPING LAYER

The main goal of this research project was to evaluate the effectiveness and integrity of the new layer of clean sediments deposited during the flood in 1996 as capping layer to contain contaminants present in the pre-existing sediments. This project, extended over 5 years, will end in November 2002. Therefore, the results presented here are preliminary as two more field work seasons will be added and much more data will be acquired to complete and confirm the assumptions.

Nonetheless, in the light of the up to date data, it is already possible to speculate on the performance of the catastrophic capping layer. For contaminants containment, the capping layer seems to trap most of them. Research is still going on to develop a model of contaminant transport throughout the flood layer which will take into consideration the effect of bioturbation. This model will allow prediction of the long-term fate of contaminants.

Another aspect of concern is the long-term physical stability of the capping layer. In fact, the layer is subjected to erosional forces (Moreau *et al*. 2000), seismic activity that is significant in this region. Urgeles *et al*. (2001) indicate that a magnitude 6.5 earthquake, which already occured in the Saguenay region, would cause submarine landslides in some areas, principally at the head of the Baie des Ha! Ha!, that could remobilize the capping layer and the underlying contaminated sediments.

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6. CONCLUSIONS

This paper has presented some results of a major project. Up to now, the flood layer, seems to be effective to contain the contaminants present in the underlying sediments. Some specific conclusions can be advanced: (1) the EM1000 multibeam sonar can be used to monitor the sediment properties evolution; (2) the thickness of the layer varies from 10 to 60 cm but can locally reach 7 m; (3) the consolidation of the layer is completed and its progression depends on the bioturbation penetration; (4) inorganic carbon content is a good tracer to identify the flood layer (5) a goechemical reactor has been defined; (6) the *Macoma calcarea* has been selected to monitor the recovery rate of the benthic ecosystem. In addition to these, a lot of work will be done in the next two years concerning the erodability, stability, fate and transport of the contaminants and evolution of the benthic community.

7. ACKNOWLEDGEMENT

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