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# Post-incident Impact Assessment of the Saguenay Flood Disaster on the Marine and Coastal Environment and Communities

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**Public Safety and Emergency Preparedness Canada**

340 Laurier Avenue West, 12th Floor
Ottawa, Ontario K1A 0P8
Tel: (613) 994-4875
Toll Free: 1-800-830-3118
Fax: (613) 998-9589
Email: communications@psepc-sppcc.gc.ca
Internet: www.psepc-sppcc.gc.ca

## Author:

Jacques Locat
Laboratoire d'études sur les risques naturels (LERN)
Groupe de recherche en géo-ingénierie et en environnement (GREGI)
Département de géologie et de génie géologique, Université Laval, Québec, G1K 7P4
Tel: (418) 656-2179, Fax: (418) 656-7339
Email: locat@ggl.ulaval.ca

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## Executive Summary

In July 1996, an exceptional climatic event left more than 200 mm of rain in the Saguenay–Lac-Saint-Jean region and had devastating effects on the people of that region as well as on the terrestrial infrastructures. Another devastating effect was the accumulation of more than 20 million tonnes of sediments in the upstream portion of the Saguenay Fjord, of which a good part came from the avulsion of the Ha! Ha! River and the intensive erosion of other major tributaries of the Saguenay Fjord region. Not long after the flood, a research team was assembled to evaluate the potentially positive impact of that disaster; the new layer of sediments had covered contaminated sediments that lie at the bottom of the fjord. This team initiated the study, *Efficiency of the catastrophic capping layer of July 1996 in acting as a barrier against contaminated sediments: an opportunity for technological advancement*.

The scientific results obtained from numerous research projects have been published as articles in many research journals or disclosed during conferences. The synopses of the symposium on the Saguenay flood, a symposium held at the onset of the project and in which OCIPEP[1] participated, are available on the Internet[2]. The last scheduled activity related to the Saguenay post-flood took place during the 2nd International Symposium on Contaminated Sediments that was held in Québec City in May 2003. This report outlines the results obtained from the special session on the Saguenay post-flood and emphasizes the various contributions and conclusions drawn from the research projects. These results will also be analyzed in light of OCIPEP's concerns.

Conclusions drawn from the various research projects include:

1. That it is possible to rapidly deploy research teams in order to estimate the effect of natural disasters on the marine environment and shoreline communities. This is due to the development and pooling of tools in the domains of chemistry, biology, geotechnics, and geophysics.

2. The layer resulting from the 1996 flood, although unevenly distributed, acted as an efficient protection layer against the migration of contaminants found in underlying sediments.

3. The repercussion of the flood on the benthic fauna has been beneficial in providing a protection layer limiting the access of these organisms to the contaminants. In the long term, this should help reduce the level of contaminants in the food chain of the animals that feed on the benthic fauna.

4. The coastal damage is limited to the areas close to river deltas.

[1] On 12 December 2003, the Office of Critical Infrastructure Protection and Emergency Preparedness (OCIPEP) was integrated into a new department, Public Safety and Emergency Preparedness Canada (PSEPC).
[2] www.ocipep.gc.ca/research/resactivites/natHaz/saguenay/1998_D001_e.asp

The local and regional infrastructures associated with the use and exploitation of the fjord's aquatic environment after the 1996 flood are finding conditions even more favourable in terms of water quality as well as benthic fauna.

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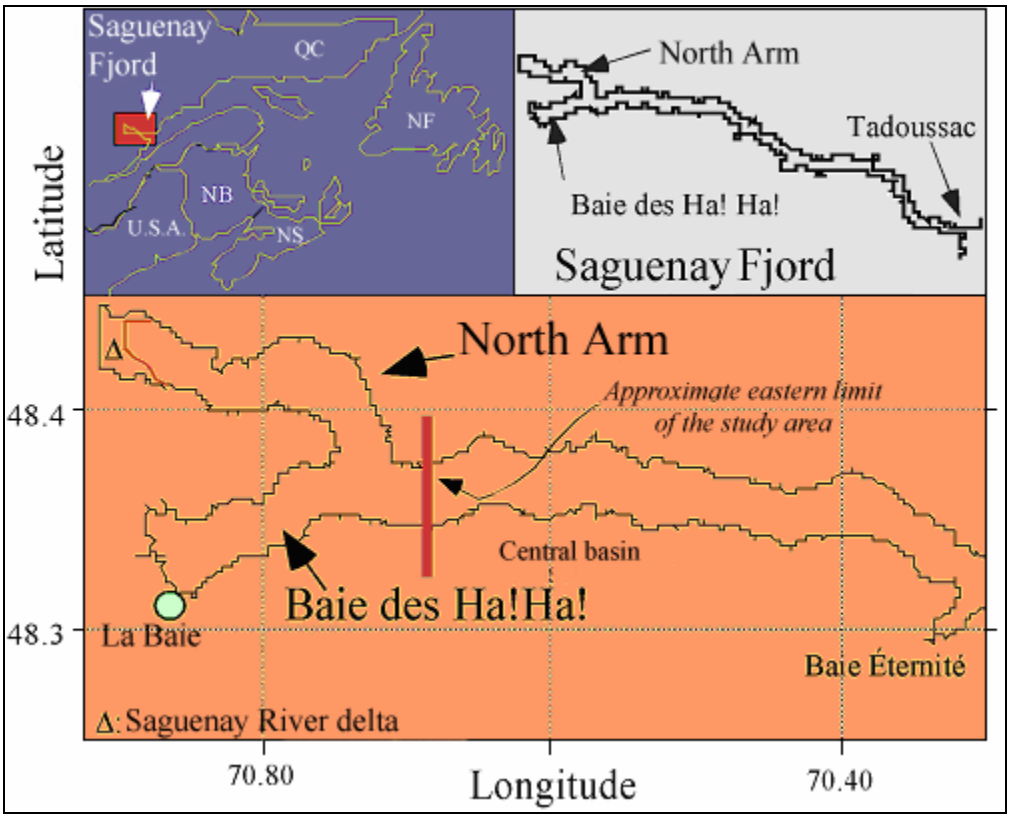
## 1.0 Introduction

In July 1996, an exceptional climatic event left more than 200 mm of rain in the Saguenay–Lac-Saint-Jean region and had devastating effects on the people of that region as well as on the terrestrial infrastructures. Another devastating effect was the accumulation of more than 20 million tonnes of sediments in the upstream portion of the Saguenay Fjord, of which a good part came from the avulsion of the Ha! Ha! River and the intensive erosion of other major tributaries of the Saguenay Fjord region (Figure 1). This catastrophic event is referred to hereafter as the Saguenay flood, and the resulting catastrophic layer is called the flood layer. This layer is approximately 20 cm thick, but it gets as thick as 5 m at the mouth of the main rivers. The extent of this layer is highlighted in Figure 2 by the dark areas that appeared in 1997.

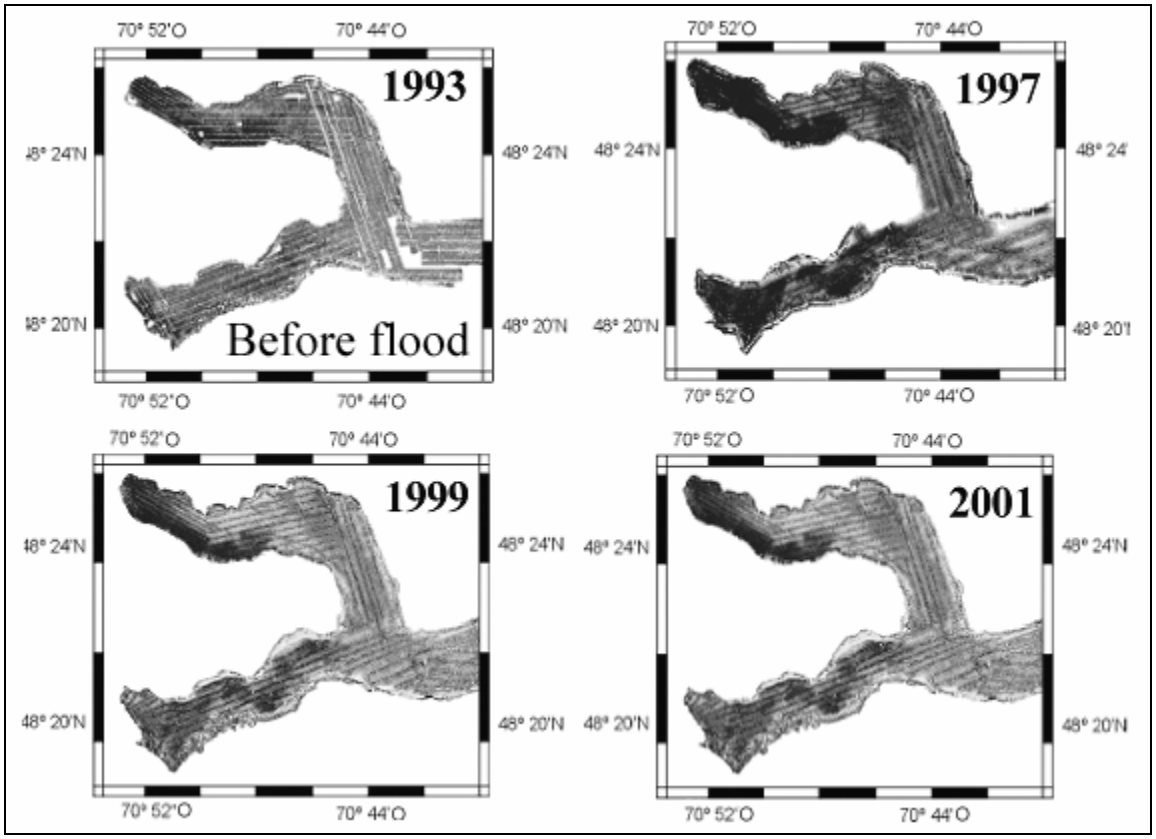
**Figure 1** View of the study area in the upstream portion of the Saguenay Fjord.




Immediately after the event, many research projects have focused on the effects of that disaster on the environment. Some of those projects have dealt with the effects of that flood on the Saguenay Fjord's ecosystem. A team of research scientists has been assembled to evaluate the potentially positive effect of that disaster, since the new sediment layer was covering contaminated sediments that lie at the bottom of the fjord. Theses scientists then started the study: *Efficiency of the catastrophic capping layer of July 1996 in acting as a barrier against contaminated sediments: an opportunity for technological advancement*. This project, referred to as the *Saguenay post-flood project*, has been financed for a period of five years (1997–2002), by the Natural Sciences and Engineering Research Council (NSERC) of Canada's strategic

program, and Alcan Inc. The major research scientists, under the supervision of Jacques Locat (Université Laval), were: Gaston Desrosiers (ISMER), Rosa Galvez-Cloutier (Université Laval), Jean-Pierre Gagné (ISMER), Yves Gratton (INRS-ETE), Philip Hill (CSC Pacific), Serge Leroueil (Université Laval), Jean-Marie Konrad (Université Laval), Bernard Long (INRS-ETE), Claude Hilaire-Marcel (UQAM), Alphonso Mucci (McGill), Émilien Pelletier (ISMER), Peter Simpkin (SEISTEK), Anne de Vernal (UQAM), and Hélène Tremblay (Université Laval).

**Figure 2** Extent of the 1996 flood layer




The initial planning of the project provided for the holding of two public workshops. The first was held in May 1998.[3] The second took place in May 2003 during the 2nd International Symposium on Contaminated Sediments, sponsored by the American Society for Testing and Materials (ASTM), the Canadian Geotechnical Society (CGS), the Canadian Society for Civil Engineering, and by the St. Lawrence chapter of SETAC (Society for Environmental Toxicology and Aquatic Chemistry). The 1998 workshop was general in nature. It allowed the integration of research problematics specific to the fjord in the overall research, and problematics identified specifically on the terrestrial side. The special session dedicated to the 2003 Saguenay post-flood, financed in part by OCIPEP, was an opportunity to share the conclusions drawn after five years of research and to share the results with the international community.

[3] Synopses of these workshops are available at:
www.ocipep.gc.ca/research/resactivites/natHaz/saguenay/1998_D001_e.asp

This report contains the results of this special session on the Saguenay post-flood project and emphasizes the various contributions and conclusions drawn from the research. These results will also be analyzed in light of OCIPEP's concerns with the management of the consequences of natural disasters, and to their effects on critical infrastructure (fishery, ecological tourism, etc.).

## 2.0 Scientific Objectives of the Saguenay Post-flood Project

The scientific objectives achieved by the project were to:

- Provide an answer concerning the efficiency of the capping layer;
- Satisfactorily identify the living species of the Saguenay Fjord that can be used as indicators of the level of environmental restoration of the site;
- Derive numerical or conceptual models enabling the evaluation and prediction of chemical reactions occurring around the capping layer;
- Provide a numerical simulation model that permits the prediction of contaminants transport through the capping layer;
- Evaluate this layer's resistance to erosion and earthquakes; and
- Group these various tools and techniques in one framework that could be used in the planning, achievement and prediction processes related to the performance of the capping layers (natural or human-made) deposited on contaminated sediments.

## 3.0 Scientific Results Disclosed during the Special Session

During the 2nd International Symposium on Contaminated Sediments, a special session was dedicated to the Saguenay post-flood project. Other results have already been published in scientific articles or disclosed during specialized conferences and have been grouped accordingly in the bibliography. In light of the framework of the 2003 special session, the majority of leading research scientists in both the private and public sectors came to share their findings. In total, 17 presentations were given; 15 were oral presentations and two were posters. Section 3.1 presents the titles of the various presentations, the author's name, and the order in which they occurred. The first is the presentation by invited participant Mr. Émilien Pelletier. The abstracts of all of the articles included in this session can be found in Appendix A.

### 3.1 Oral Presentations

1. The origin and behavior of a catastrophic capping layer deposited on contaminated sediments of the Saguenay fjord (Quebec); É. Pelletier, G. Desrosiers, J. Locat, A. Mucci, and H. Tremblay.

2. Execution of the Saguenay post-flood project: a unique project with exceptional people; J. Locat , H. Tremblay, R. Galvez-Cloutier, G. Desrosiers, J.P. Gagné, Y. Gratton, P. Hill, J.-M.Konrad, S. Leroueil, B. Long, C. Hilaire-Marcel, A. Mucci, E. Pelletier, P. Simpkin and A. de Vernal.

3. Results from multibeam, sedimentological and geotechnical data of the "Saguenay Project"; R. Urgeles and J. Locat.

4. Retention of Heavy Metals in the Post '96 Flood Sediment Layer Deposited in the Saguenay River, Quebec, Canada; R. Galvez-Cloutier, M. Muris, J. Locat, and C. Bourg.

5. Evolution of persistent organic pollutants (POP) in the sediments of the Baie des Ha! Ha! after the 1996 flood; M. Leboeuf, M. Noël, and S. Trottier.

6. Characterization of a Catastrophic Flood Sediment Layer: Geological, Geotechnical, Biological, and Geochemical Signatures; H. Tremblay, G. Desrosiers, J. Locat, A. Mucci, and É Pelletier.

7. In situ Flume measurements of sediment erodability in Saguenay Fjord (Quebec, Canada) A-L. Moreau, J. Locat, P. Hill, B. Long, and Y. Ouellet.

8. Trace Metal Mobility In Sediments Following A Catastrophic Depositional Event; A. Mucci, C. Guignard, and G. Bernier.

9. Factors controlling contaminant transport through the flood sediments of the Saguenay Fjord: Numerical sensitivity analysis; S. Dueri and R. Therrien.

10. Monitoring the origin, reactivity and residence time of suspended particulate matter in transitional environments using Th isotopes (234Th, 232Th, 230Th, 228Th) – Example from the Saguenay Fjord (Québec); P. Poulin, B. Ghaleb, C. Hillaire-Marcel, and A. Mucci.

11. Physical, magnetic, sedimentological, geochemical, isotopic and micropaleontological features of rapidly deposited layers in the Saguenay Fjord, Québec from 7200 cal BP to the 1996 AD flood layer; G. St-Onge, G. Bilodeau, A. de Vernal, C. Hillaire-Marcel, B. Ghaleb, J. Leduc, A. Mucci, J. Savard, D. Zhang, T. Mulder, D. Piper, and J. Stoner.

12. A complete re-assessment of polycyclic aromatic hydrocarbons (PAHs) in sediments of the Saguenay Fjord (Quebec); É. Pelletier, N. Côté, A. Curtosi, and R. St-Louis.

13. Selective extraction of polycyclic aromatic hydrocarbons (PAHs) from contaminated sediments using a high molecular weight surfactant; M. Barthe, and É. Pelletier.

14. Kinetics and mechanisms of polyaromatic hydrocarbons (PAH) sequestration in freshwater and marine sediment; D. Brion and É. Pelletier.

### 3.2 Poster Session

- Behaviour of high molecular weight PAHs in the new sediment layer of the Baie des Ha!Ha! (Saguenay Fjord); É. Pelletier and I. Desbiens.

- Contributions of the Saguenay post-flood project to the design of capping layers; H. Tremblay and J. Locat.

### 3.3 Other Scientific Documents

During the 2nd International Symposium on Contaminated Sediments, two documents comprising a collection of articles and long-form abstracts have been published. These documents are the following:

- Locat, J., Galvez-Cloutier, R., Chaney, R., and Demars, K. (Editors), 2003. Contaminated Sediments: Characterization, Evaluation, Mitigation, Restauration and Management Strategy Performance. American society for Testing and Materials, Special Technical Publication 1442, 321 p.

- Tremblay, H., Locat, J. and Galvez-Cloutier, R., (authors) 2003. Transactions of the 2nd International Symposium on Contaminated Sediments, Québec, May 2003. CD-ROM.

In total, these two documents contain more than 90 complete articles and long-form abstracts on the topic of contaminated sediments.

## 4.0 Scientific Benefits of Research

In addition to meeting the previously stated objectives, the project also had scientific benefits, including:

- Definition of a new reference (1996 layer) enabling a more precise identification of the addition of contaminants in the Saguenay Fjord after the 1996 flood.

- Definition of the optimum conditions (minimum thickness of the layer that can effectively block the chemical and biological migration of the toxic substances trapped) for a possible capping of a layer of contaminated sediments by a layer of clean sediments in a deep marine area. These data could be used immediately in the remedial process in the Baie des Anglais at Baie-Comeau.

- Unique and diversified data combined in an interactive database on the Internet.

- Characterization of geochemical, mechanical and biological environmental recovery indicators.

- Development of planning and designing tools for a capping layer of contaminated sediments.

- Use of EM1000 and EM3000 to map and track the capping layers.

## 4.1 Considerations of the Marine and Coastal Effects of the July 1996 Flood

The various tasks accomplished in the upstream portion of the Saguenay after the July 1996 flood enable us to draw a few observations with regard to the actual and future effects of the Saguenay flood on the marine ecosystem and coastal infrastructures.

### 4.1.1 Marine Environment

In the marine environment, the Saguenay flood has put in place a capping layer that has momentarily disrupted the benthic fauna to such an extent that it almost completely disappeared from many sectors of the Baie des Ha! Ha! and of the North Arm. However, our studies clearly indicate that the rehabilitation of the benthic fauna has been very rapid. In less than two years, the majority of the study stations were showing an occupancy level similar to the one before the flood.

The various studies conducted have enabled the validation of the underlying hypothesis which stated that the July 1996 flood layer would act as an efficient protection layer against the migration of contaminants from the sediments present before the July 1996 flood.

The natural hazards analysis conducted in that region also showed that it would take an earthquake magnitude of 7.0 or more to perturb the 1996 layer, and that it would only occur in limited sectors.

Because of the mechanical (consolidation) and biological (bioturbation) stabilization, the capping layer becomes more resistant, particularly in the Baie des Ha! Ha!, to erosion and the normal currents do not succeed in eroding it. However, it is also important to note that the marine environment of the North Arm is much more dynamic. Our studies indicate that there have been sectors of the North Arm where there was erosion in the presence of strong currents coming from the Saguenay River and a re-deposition a bit further downstream. Given those conditions, the performance of the 1996 layer is more difficult to demonstrate in that sector.

The long-term performance of the 1996 flood layer as a whole will thus greatly depend on the future seismic activity; the only triggering factor capable of mobilizing large surfaces. Locally, the anchoring of large vessels in the outer bay of La Baie could also disrupt the surface layer in the long term.

In light of the various studies conducted, it appears that the aquatic and depositional environments came out of that disaster in better shape than before. As for the fjord, the assessment of the consequences of the catastrophic flood of 1996 has allowed us to point out the improvement in quality of the marine environment. Hence, the source of contaminants coming from the Baie des Ha! Ha! is in good part trapped under the 1996 layer. Correspondingly, the

quality of the water and of the benthic fauna should support the development of infrastructures associated with that region of the fjord, such as ice fishing, recreational activities, and any other industry that uses the water body.

### 4.1.2 Coastal Environment

The coastal environment was affected by the flood, especially by the accumulation of sediments and debris resulting from the erosion of rivers. An example of this is the filling of the Grande Baie marina.

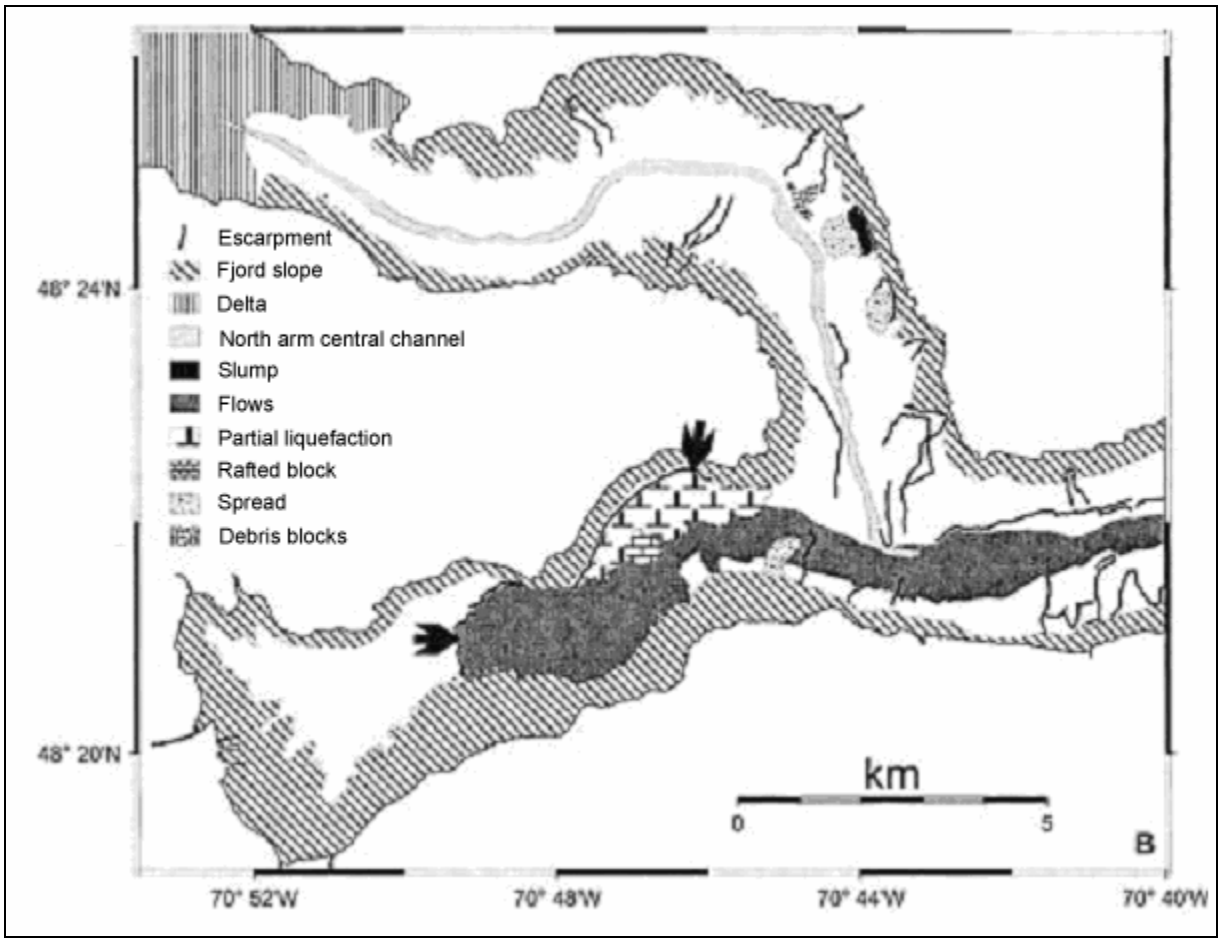
The addition of sediments has contributed to push the edge of the rivers' delta offshore, namely that of the Ha! Ha! River. The rapid accumulation of sediments has also favoured the development of areas of instability. These areas will most likely be more at risk in the event of a major earthquake (magnitude of seven or greater if the epicentre is located in the area (see Figure 4).

Research dealing with the response of the Saguenay sediments after an earthquake has enabled scientists to emphasize the morphological and analytical indications that lead us to believe that the epicentre of the 1663 earthquake could be located in the Saguenay region, rather than Charlevoix.

### 4.1.3 Landslides Hazard

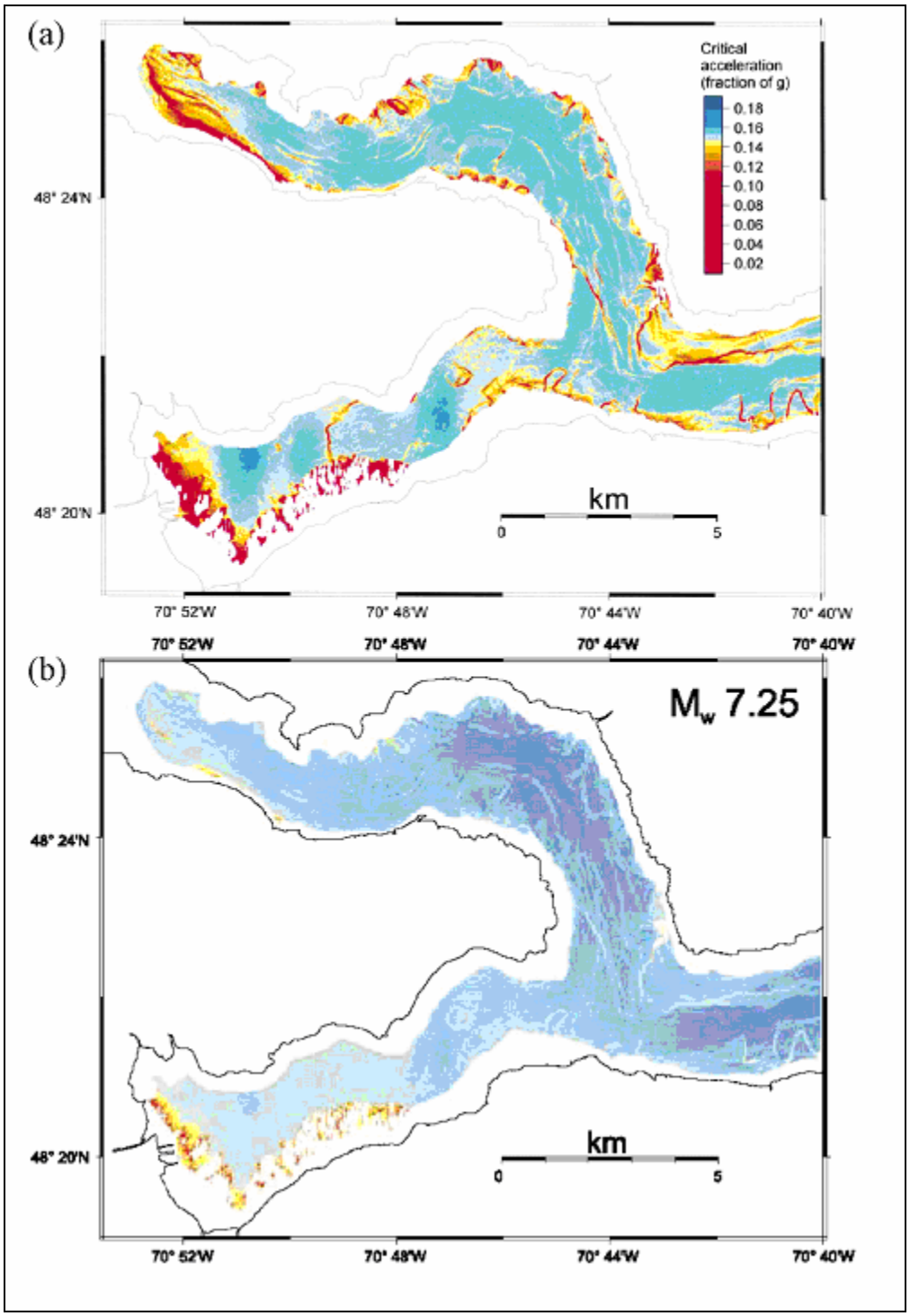
The means put forward to study the 1996 flood layer and its fate have allowed us to acquire a better understanding of the hazards related to landslides. For example, the analysis allowed the accounting of landslides in the upstream portion of the fjord (Figure 3) while highlighting important mass wasting, the majority of which would have been triggered by the 1663 earthquake.

**Figure 3** Known extents of landslides potentially related to the 1663 earthquake (Urgeles *et al*., 2002a).




The analysis of regional data on critical accelerations has been evaluated and compared to the properties of the surface layers of the Saguenay Fjord in order to evaluate the critical thresholds of seismic acceleration that can provoke instabilities (Figure 4a). From this analysis, it has been possible to conclude that only a major earthquake of a magnitude of 7.0 or more could destabilize the surface sediments and that the areas affected would be minimal, as shown in Figure 4b.

**Figure 4** Effects of an earthquake on the surface sediments in the upstream portion of the Saguenay Fjord (a) critical acceleration required to create instability, and (b) potential instability area left by an earthquake of an intensity of 7.3 (modified according to Urgeles *et al*., 2002a).



## 5.0 Conclusion on the Marine and Coastal Effects of the Saguenay Flood

In light of the research results presented at the special session on the Saguenay post-flood project during the 2nd International Symposium on Contaminated Sediments, conclusions can be drawn on the effects observed on the marine and coastal environments and recommendations made with regard to future research priorities in the Saguenay Region.

### 5.1 Effects on the Marine and Coastal Environments

The studies conducted in the upstream portion of the Saguenay Fjord allow the following conclusions:

1. The layer resulting from the 1996 flood, although unevenly distributed, acted as an efficient protection layer against the migration of contaminants found in underlying sediments.

2. The impact of the flood on the benthic fauna has been beneficial in providing a protection layer limiting the access of these organisms to the contaminants, in the long run this should help reduce the level of contaminants in the food chain of the animals feeding on the benthic fauna.

3. The coastal damage is limited to the areas close to river deltas.

4. The local and regional infrastructures associated with the use and exploitation of the fjord's aquatic environment found conditions even more favourable in terms of water quality as well as benthic fauna after the 1996 flood.

It is possible to rapidly deploy research teams to estimate the effect of natural disasters on the marine environment and on the shoreline communities because of the development and pooling of tools in the areas of chemistry, biology, geotechnics and geophysics. This is highly applicable, even in the area of emergency preparedness.

### 5.2 Future Research Priorities in the Saguenay Region

Work done in relation to the Saguenay post-flood project has enabled scientists to prioritize future research work as follows:

1. Regular monitoring of the stability of the slope in the straight portion of the actual deltas, namely that of the Ha! Ha! River.

2. Evaluation of the paleoseismicity of that region in order to gain knowledge about seismic hazard and to be able to include it in the risk evaluation in the marine as well as coastal environments.

3. Evaluation of the impact of ships on the remobilization of contaminated sediments.

These research activities could help communities gain knowledge about the actual risks in that region – the more susceptible areas as well as triggers. The effects of another event similar to the Saguenay flood could then be mitigated.

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# Appendix A – Abstracts for the Special Session on the Saguenay Post-flood Project

This appendix contains the abstracts of all of the articles and posters relating to the special session on the Saguenay post-flood project. The long-form abstracts and/or complete articles may be found in STP-1442 or in the Symposium Transactions, as applicable.

## *Oral Presentations*

### The Origin and Behaviour of a Catastrophic Capping Layer Deposited on Contaminated Sediments of the Saguenay Fjord (Quebec)

Emilien Pelletier[1], Gaston Desrosiers[1], Jacques Locat[2], Alfunso Mucci[3] and Hélène Tremblay[2]
[1] Institut des sciences de la mer (ISMER), Université du Québec à Rimouski, Rimouski (Que) Canada
[2] Département de géologie et génie géologique, Université Laval, Québec (Que), Canada
[3] Department of Earth & Planetary Sciences, McGill University, Montreal (Que) Canada

ASTM STP 1442

ABSTRACT: The upper section of the Saguenay Fjord was impacted by a catastrophic flood in July 1996. Contaminated sediments were capped by a layer of clean silty post-glacial sediments with very low levels in trace metals (Cu, Cd, Cr, Hg, Pb, and Zn) and polycyclic aromatic hydrocarbons (PAHs). The capping layer was characterized by geotechnical and geochemical methods and its biological recolonization was monitored by annual sampling of the macrofauna. The consolidation of the layer was completed within 3 months. The strong dominance of surface deposit feeders Cirratulidae and Ampharetidae was observed at most stations in the first 2-3 years followed by carnivorous annelids such as Lumbrineridae and Nephtidae; species indicating a well recolonized benthic habitat in the Baie des Ha! Ha!. The slope stability of the capping layer is considered as very good except in limited deltaic sectors at the head of the Baie des Ha! Ha! The new layer showed a good efficiency to isolate contaminated sediments from the Saguenay deep waters. Although manganese and iron were remobilized as the new layer became anoxic, mercury, arsenic and PAHs showed a very limited mobility through the flood layer.

**Execution of the Saguenay post-flood project: a unique project with exceptional people**

Jacques Locat[1], Hélène Tremblay[1], Rosa Galvez-Cloutier[1], Gaston Desrosiers[2], Jean-Pierre Gagné[2], Yves Gratton[3], Philip Hill[4], Jean-Marie Konrad[1], Serge Leroueil[1], Bernard Long[3], Claude Hilaire-Marcel[5], Alfonso Mucci[6], Émilien Pelletier[2], Peter Simpkin[7], Anne de Vernal[5]
[1] Département de Géologie, Université Laval, Sainte-Foy, Québec, Canada
[2] Institut des Sciences de la mer de Rimouski, Université du Québec à Rimouski, Rimouski, Québec, Canada
[3] INRS-ETE, Québec, Canada
[4] Commission géologique du Canada, région du Pacifique
[5] Université du Québec à Montréal
[6] Department of Earth & Planetary Sciences, McGill University, Montreal (Que) Canada
[7] Simpkin Inc

ABSTRACT: The Saguenay post-flood project was carried out during the period from 1997 to 2003. It has assembled many researchers who had to evaluate the performance of the 1996 flood layer to act as a barrier to the movement of the underlying contaminants and to develop various tools aimed at evaluating or monitoring the performance of this catastrophic barrier. After five years of research, we can conclude that this layer is efficient and shall resist most of the natural processes that could modify it with the exception of a large earthquake but even then the effects would be local. This work has required the participation of many universities and government organizations and has offered to possibility to train or educate more than 42 graduate students including 17 Ph.D's. The overall goal could be achieve not only from the direct funding but also from the previous knowledge acquired over the previous years by researchers which has enabled us to carry out the project at a total cost of about 1.3 million dollars. Major spin-offs from the Project not only consist in the data base but also in the increase knowledge that was gained of the various processes which are taking place here and moreover of the international recognition of the Saguenay Fjord as a major natural laboratory.

**Evolution of the benthic populations after the flash flood of 1996 in the Baie des Ha! Ha!; Saguenay fjord (Quebec)**

Gaston Desrosiers[1], Matthieu Gonon[1], Laure de Montety[1], Émilien Pelletier[1], Christian Nozais[1], Emma Michaud[2], Georges Stora[2], Bernard Long[3], Hélène Tremblay[4], Jacques Locat[4]
[1] Institut des Sciences de la mer de Rimouski, Université du Québec à Rimouski, Rimouski, Québec, Canada
[2] Laboratoire d'Océanographie et de Biogéochimie, Université de la Méditerranée, COM, Campus de Luminy, Marseille, France
[3] INRS-ETE, Québec, Canada,
[4] Département de Géologie, Université Laval, Sainte-Foy, Québec, Canada

ABSTRACT: Following a flash flood which occurred in the Saguenay area in July 1996, the bottom of the Baie des Ha! Ha! was covered by a large quantity of new sediments. Its thickness decreased from the head of the bay towards the mouth. Perturbations in the benthic macrofauna resulting from this event have been more important in stations located near the mouth of the Rivière des Ha! Ha!. A 5-year benthic monitoring study was carried out at 5 stations (annual sampling). It has shown a re-colonization process of the new sediment layers mainly by

polychaetes. A different succession was observed for the major polychaete species between the stations located at the head of the bay and to the other sites. This succession was linked to the decrease of the deposit layer thickness. At station 2, the benthic macrofauna was mainly composed by deposit feeder. On the other hand, stations 5, 7, 9 and 13 were colonized by the subsurface deposit feeder *Scoloplos armiger* and carnivorous like *Lumbrinereis fragilis*. Statistical analysis showed that station 2 evolved differently from the other studied stations.

**Results from multibeam, sedimentological and geotechnical data of the 'Saguenay Project'**

Roger Urgeles[1], Jacques Locat[2]
[1] GRC Geociències Marines, Departament d'Estratigrafia, Paleontología i Geociències Marines, Universitat de Barcelona, Campus de Pedralbes, 08028 Barcelona (Catalonia), Spain
[2] Département de géologie et de génie géologique, Université Laval, Ste.-Foy, Québec, Canada

ABSTRACT: In July 1996 a major flooding of the Saguenay region caused the delivery of a large amount of sediments to the Saguenay Fjord, which buried the former contaminated sediments. Several multibeam and sampling surveys where triggered by the flood which aimed to understand the concealing ability of the newly deposited sediments. These surveys showed the effects of the flood on the Fjord bottom but also the existence of older mass movements. Nevertheless a dynamic slope stability analysis showed that the fjord sediments are stable within the recurrence interval of major earthquakes. The backscatter strength from the multibeam data also showed the evolution of the flood layer, though to represent the wiping out of benthic life and the subsequent recolonization of the flood layer by the benthos.

**Retention of Heavy Metals in the Post '96 Flood Sediment Layer Deposited in the Saguenay River, Quebec, Canada**

Rosa Galvez-Cloutier[1], Myriam Muris[2], Jacques Locat[3], Cyril Bourg[2]
[1] Dept. of Civil Engineering. Laval University, Quebec, Canada
[2] Ecole Nationale de Travaux Public de l'État, Lyon, France
[3] Department of Geology, Laval University, Quebec, Canada

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ABSTRACT: In July 1996 during a 50-year event flood, a new layer of sediments composed of debris, gravel and fine materials was transported and deposited over an ancient, one meter contaminated layer of sediments in the Saguenay River Fjord and Ha! Ha! Bay floors. During the Industrial Revolution years, various metallurgic, plastic, aluminum and pulp and paper production industries discharged their wastes on these waters, resulting in the high contamination of both water and sediments. This contamination limited the exploitation of fish and seafood. Given that the new layer is composed essentially of cleaner material, the zone is presenting important changes in the direction of a healthier environment. The Canadian Government and some of the surrounding industries aim to assess the new potential of the zone and its environmental safety. At present, it represents over a million-dollar study. This part of the Saguenay project aimed to recognize and evaluate the capacity of the new layer to contain and retain the contaminants left at the bottom layer. Particular interest is given to mercury and to

heavy metals such as Pb, Zn, Cd, and Ni and to their geochemical distribution among natural adsorbing materials such as clays, oxides, carbonates and organic matter. The paper presents the recognition and sampling mission on the Alcide Horth Ship, the contamination profiles given in two dimensions (length and depth), the geochemical distribution of heavy metals on the contaminated layer, transition layer and new layer as well as the evolution of their retention and transfer. Discussion and relations with common sediment characteristics such as grain size, cation exchange capacity and surface area are also given. Sequential selective extraction has been used jointly with scanning electron microscopy (SEM) to study heavy metal species.

**Evolution of persistent organic pollutants (POP) in the sediments of the Baie des Ha! Ha! after the 1996 flood**

Michel Lebeuf, Michelle Noël et Steve Trottier
Institut Maurice-Lamontagne, Ministère des Pêches et des Océans, Québec, Canada

ABSTRACT: In July 1996, a deluge of rain carried tonnes of soil into surface waters of the Saguenay region. Baie des Ha! Ha! and the North Arm of the Saguenay River were amongst the most affected areas. At some locations within the bay, sedimentary depositions exceeded 20 cm. This natural catastrophe has offered an exceptional opportunity to study the fate of persistent organic pollutants (POPs) buried by new sediments. In 1997, a study was initiated in order to characterise the levels and patterns of POPs in both new and old sediments. A 45 cm long sediment core was collected from Baie des Ha! Ha! and then sectioned in more than 20 layers. Water content and $^{210}$Pb activity measured in the sediment layers allowed to estimate the thickness of the new sediment to about 20 cm. Concentrations of polychlorinated biphenyls (PCBs) and organochlorinated pesticides (OCs) measured in the new sediments were approximately ten times lower than maximum concentrations in sediments deposited prior to the 1996 flood. In addition, new sediment cores collected in 1999 and 2000 allowed us to monitor the changes in distribution of PCBs and OCs in both new and old sediments. Results indicated that within this time frame, POPs were barely mobile within sediments of Baie des Ha! Ha!. Apparently, the new sediment layer moves away and isolates POPs from the water-sediment interface, reducing their access to benthic organisms and their transfer to the food web.

**Characterization of a Catastrophic Flood Sediment Layer: Geological, Geotechnical, Biological, and Geochemical Signatures**

Hélène Tremblay[1], Gaston Desrosiers[2], Jacques Locat[1], Alfunso Mucci[3], Émilien Pelletier[2]
[1] Département de géologie et de génie géologique, Université Laval, Ste.-Foy, Québec, Canada
[2] Institut des Sciences de la mer de Rimouski, Université du Québec à Rimouski, Rimouski, Québec, Canada
[3] Department of Earth and Planetary Sciences, McGill University, Montreal, Qc, Canada

ASTM STP 1442

ABSTRACT : In 1996, an important rainstorm took place in the Saguenay region, Canada, that caused sever flooding and erosion of a large amount of post-glacial sedimentary material. Consequently, about 20 million tonnes of sediment were deposited in the upstream part of the

Saguenay Fjord, covering the recent, contaminated sediments with a 10 to 60 cm thick layer of relatively clean material. This flood layer was distinguished from the pre-flood sediments by various properties: low consistency and low resistance, high water content, the absence of benthic organisms, or the presence of inherited geochemical components. In this study, we evaluated the criteria used by the various investigators to identify the 1996 flood deposit, then finally compared its signature. Subsequently, we assessed the spatial variability of the deposit and its effect on the interpretation of temporal studies.

**_In situ_ Flume measurements of sediment erodability in Saguenay Fjord (Quebec, Canada)**

Ann-Laure Moreau[1], Jacques Locat[1], Phillip Hill[2], Bernard Long[3], Yvon Ouellet[4]
[1] Department of Geology and Geological Engineering, Laval University, Quebec, Canada,
[2] Natural Resources Canada, Geological Survey of Canada, Sidney, B.C.
[3] INRS-ETE, Québec, Canada
[4] Civil Engineering department, Laval University, Quebec, Canada,

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ABSTRACT : The erodability of superficial sediments in Saguenay Fjord, Quebec, was investigated during three years at 14 sites in the Baie des Ha!Ha! and the North Arm. This was carried out using a benthic flume: the *Miniflum*e. Previous studies showed that the characteristics of the Saguenay fjord sediments varied greatly on small and large scales. The critical shear stresses and the erosion rates reflect this variability, with critical shear stresses ($\tau_c$) between 0.06 and 0.44 Pa and mean erosion rates for the total erosion phase ($E_{mean}$) between $3.4 \times 10^{-4}$ and $1.25 \times 10^{-5}$ kg.m$^{-2}$.s$^{-1}$. The measured critical shear stresses and rates were consistent with those of other *in situ* studies. Variability of the results is linked to important spatial variabilities of benthic sediments and not to temporal variabilities. Identification of erosion parameters (critical shear stresses and erosion rates) and of their important variability is the first step in determining the hazard linked to the erosion susceptibility of sediments in the Saguenay Fjord.

**Trace Metal Mobility in Sediments Following a Catastrophic Depositional Event**

Alfonso Mucci, Constance Guignard, and Geneviève Bernier
Department of Earth and Planetary Sciences, McGill University, Montreal, Qc, Canada

ABSTRACT: Following the flash floods of July 1996, several million tons of post-glacial sediments were eroded and carried to the Saguenay Fjord (Quebec, Canada). Tens of centimeters of this material were rapidly deposited on top of the contaminated sediments of the Fjord. Although the flash flood left more than $2 billion (CAN$) in damages on land, it was postulated that this sudden influx of post-glacial sediments may inhibit the remobilization of contaminants associated with the indigenous sediment.

The vertical distribution and concentrations of Fe, Mn, As and Hg were measured in the pore waters and sediments recovered from box-cores taken each year since the flood along the main axis of the Fjord and in the Baie des Ha! Ha!. Time series analyses reveal that manganese remobilization was unaffected by the accumulation of the flood deposits. Authigenic manganese

oxyhydroxides present at the original sediment-water interface and the flood material were reduced and Mn(II) diffused almost freely to the newly established interface where it was oxidized and precipitated. In contrast, iron associated with the authigenic oxyhydroxides at the original interface was trapped as sulfides under the sulfate-reducing conditions that were rapidly established. Most of the arsenic and mercury associated with the pre-flood sediments also appear to have been trapped with the authigenic sulfides (i.e., AVS), thus limiting their diffusion through the flood deposit.

**Factors controlling contamiant transport through the flood sediments of the Saguenay Fjord : Numerical sensitivity analysis**

Dueri, S. and Therrien, R., Département de Géologie et génie géologique, Université Laval, Québec, QC, Canada

ASTM STP 1442

ABSTRACT: In July 1996, two days of intense rainfall caused severe flooding in the Saguenay region and led to the discharge by rivers of several million cubic meters of clean sediments to the Fjord. This turbidite layer, composed of clean sediments, represents a potential barrier for the migration of heavy metals and PAHs from the underlying contaminated sediments towards the new sediment-water interface. A numerical model has been developed to simulate the vertical migration and remobilization of dissolved contaminants in the capping layer. The model includes the main physical, chemical and biological factors affecting the contaminant flux in the cap. Calibration of the model has been achieved through comparison with the data collected during the field and laboratory characterization of the sediments of the Saguenay Fjord. A detailed sensitivity analysis, based on factorial design, shows that the model parameters associated with bio-irrigation have the greatest impact on the model output and by extension on the effectiveness of a capping layer.

**Monitoring the origin, reactivity and residence time of suspended particulate matter in transitional environments using Th isotopes (234Th, 232Th, 230Th, 228Th) – Example from the Saguenay Fjord (Québec)**

Patrick Poulin, Bassam Ghaleb, Claude Hillaire-Marcel and Alfonso Mucci
GEOTOP – UQAM & McGill

ABSTRACT: In the Saguenay Fjord the pycnocline, which separates the fresh water of the Saguenay River from the marine water that originates from the St. Lawrence estuary, displays high concentrations (2-5 mg/L) of suspended particulate matter (SPM). This SPM is the locus of a number of processes, including adsorption, desorption and coagulation, that play a major role on the fate of contaminants in the fjord. In this study, we pay special attention to the composition (i.e., organic/inorganic) and mineralogy of the SPM, to its adsorption of short-lived thorium isotopes ($^{228}$Th and $^{234}$Th), produced by the decay of dissolved $^{228}$Ra and $^{238}$U, respectively, as well as to its content in other Th isotopes ($^{230}$Th-$^{232}$Th) in relation to its mineralogy, grain size and origin (*i.e.*, Precambrian *vs.* Paleozoic bedrocks or Quaternary deposits). The primary objective of the study is to document the residence and/or transit time of the SPM in the Fjord, as

well as to assess scavenging rates of heavy metals, based on the ratios of short-lived Th isotopes to the other isotopes of the element.

SPM samples were collected from large volumes of water (300-600 L) taken at the pycnocline, and concentrated by tangential filtration. Sampling was conducted in May and September 2001 with the complementary goal to understand the impact of seasonal hydrographic variations on SPM composition and fluxes and on Th-isotope scavenging rates. The isotopes were analyzed by alpha ($^{230}$Th-$^{232}$Th-$^{228}$Th) or beta ($^{234}$Th) spectrometry. Complementary analyses included measurements of organic carbon and total nitrogen contents, $^{13}$C and $^{15}$N-isotope compositions, and semi-quantitative mineralogical analysis by X-ray diffraction.

Results show that the organic fraction of the SPM consists primarily of algal and bacterial material produced within the Fjord or upstream in the Saguenay River. The mineral fraction of SPM is essentially inherited from the migmatites of the Precambrian basement. $^{234}$Th, $^{232}$Th, $^{230}$Th, and $^{228}$Th activities in SPM increase from the head towards the outlet of the Fjord and display a seasonal pattern. The downstream increase in $^{232}$Th and $^{230}$Th, is interpreted as a consequence of the decreasing grain size of the particles. The increase in $^{234}$Th and $^{228}$Th (relative to $^{232}$Th) is the result of subsequent adsorption of these isotopes produced *in-situ* by the decay of dissolved $^{238}$U and $^{228}$Ra, respectively, $^{228}$Th/$^{232}$Th ratios vary seasonally and spatially between 0.5 and 2, with up to a 2 fold increase downstream relative to the head of the Fjord. $^{234}$Th/$^{232}$Th activity ratios as high as 80 are observed in the SPM recovered from the pycnocline, indicating a high production rate in the overlying surface water and an efficient adsorption/scavenging of $^{234}$Th. In order to estimate transit or residence times of SPM, through the Fjord, we assumed a constant $^{238}$U/$^{228}$Ra ratio in the surface water layer, thus a constant ratio between the production rates of $^{234}$Th and $^{228}$Th ($R_0$). The ratio (R) between the excess $^{234}$Th and $^{228}$Th in the SPM was used to calculate a transit time $t = Ln(R_0/R)*[1/(\lambda_{234}-\lambda_{238})]$, where $\lambda_{234}$ and $\lambda_{238}$ are the decay constants of $^{234}$Th and $^{228}$Th, respectively. Since $\lambda_{234} >> \lambda_{238}$, $t \sim Ln(R_0/R)*1/\lambda_{234}$. Residence or transit times ranging from 3 to 21 days, were obtained. Measurements of $^{238}$U and $^{228}$Ra in the water column are planned in order to validate this approach. Delayed measurements of $^{228}$Th/$^{232}$Th ratios in aliquots of SPM collected in year 2001 are in progress and will provide insights into the initial $^{228}$Ra/$^{232}$Th disequilibria in SPM, due to $^{228}$Ra losses.

**Physical, magnetic, Sedimentological, GEOCHEMICAL, isotopic and micropaleontological features of rapidly deposited layers in the Saguenay Fjord, Québec: from 7200 cal BP to the 1996 AD flood layer**

Guillaume St-Onge[1], Guy Bilodeau[1], Anne de Vernal[1], Claude Hillaire-Marcel[1], Bassam Ghaleb[1], Julie Leduc[1], Alfonso Mucci[1], Josée Savard[1], Deke Zhang[1], Thierry Mulder[2], David Piper[3], Joseph Stoner[4]
[1] GEOTOP-UQÀM-McGill, Montréal, QC, Canada
[2] Université de Bordeaux 1, Talence, France
[3] Geological Survey of Canada (Atlantic), Dartmouth, NS, Canada
[4] INSTAAR, University of Colorado, CO, USA

ABSTRACT: Sedimentological, geochemical, isotopic and micropaleontological properties of surface and sub-surface sediments cored in the Saguenay Fjord and adjacent Baie des Ha!Ha! allowed the identification of several rapidly deposited layers (RDL). The most recent ones in box-cored sediments include layers deposited during the 1996 AD flood, the 1988 AD earthquake and the 1971 AD landslide of St-Jean-Vianney. Short-lived isotope ($^{228}$Th, $^{210}$Pb and $^{137}$Cs) measurements suggest discrete mixing, notably on top of these layers, but all were buried rapidly enough to preserve most of their original isotopic signature. Analyses of foraminifers collected before and after the 1996 AD flood indicate that the recolonization of surface sediments by the benthic microfauna was almost immediate, with increased species diversity as compared to pre-flood sediments, suggesting that the 1996 AD flood layer has played a role in isolating the underlying contaminated sediments. A total of 14 RDL likely resulting from high magnitude (>6) earthquakes during the last ~7200 calibrated years BP were also recognized in a 38 m-long piston core from the inner basin of the Fjord. They include an approximately 16 m-thick layer associated with the great historical earthquake of 1663 AD.

**A complete re-assessment of polycyclic aromatic hydrocarbons (PAHs) in sediments of the Saguenay Fjord (Québec)**

Émilien Pelletier, Nathalie Côté, Antonio Curtosi, Richard St-Louis
Institut des Sciences de la Mer de Rimouski, Université du Québec à Rimouski
Rimouski, QC, Canada

ABSTRACT: The objective of this work is to provide a new series of data on the spatio-temporal distribution of PAHs in sediments of the Saguenay Fjord and the Baie des Ha!Ha! about 15 years after the last exhaustive report on the topic. Five sediment cores have been sampled from various sectors of the Fjord in Spring 2002 and analysed for their content in PAHs by GC/MS. Total PAHs (selected 16 priority HAPs) are reported for the first 28 cm of each core. The mean concentration in the surface layer (0.0-0.5 cm) was 310 ng/g (dry weight) with a maximum value of 460 ng/g found at core 5 in the North Arm of the Fjord and a minimum value of 227 ng/g found in the Baie des Ha!Ha!. Surface values reported here are between 10 and 30 times lower than those previously reported for cores sampled in 1982 (Martel et a. 1987). All cores show maximum PAHs values in layers between 15 and 28 cm depth indicating a slow burying process of highly contaminated sediments brought to the fjord in the 1960s and 1970s.

**Selective extraction of polycyclic aromatic hydrocarbons (PAHs) from contaminated sediments using a high molecular weight surfactant**

Mickaël Barthe, Émilien Pelletier
Institut des Sciences de la Mer de Rimouski, Université du Québec à Rimouski
Rimouski, QC, Canada

ABSTRACT: The objective of the project was to develop a selective extraction method for PAHs that could mimic the digestive action of microorganisms and benthic invertebrates and contribute to understand the influence of chemical sequestration on the bioavailability and the toxicity of organic molecules present in marine sediments. Preliminary tests to determine the selectivity and efficiency of a series of surfactants led us to the choice of the polyoxyethylene(100) stearyl ether (Brij® 700) with an optimum concentration of $5.25 \times 10^{-3}$ M. Results obtained with Brij® 700 show that the development of a selective extraction method of PAHs using a high molecular weight synthetic surfactant presenting some similarities with natural surfactants produced by microbial communities can provide relevant data that can be related to sequestration mechanisms. Our protocol was tested with 17 samples from the Saguenay Fjord. In a general manner, the high-molecular weight PAH compounds were less extracted by Brij® 700 than the low-molecular weight PAH compounds.

**Kinetics and mechanisms of polyaromatic hydrocarbons (PAH) sequestration in freshwater and marine sediment**

Denis Brion, Émilien Pelletier
Institut des Sciences de la Mer de Rimouski, Université du Québec à Rimouski
Rimouski, QC, Canada

ABSTRACT: Polycyclic aromatic hydrocarbons (PAH) are known to be persistant in marine and freshwater sediments. An aging process often called sequestration is responsible for the change in the availability of PAHs and is attributed to a slow migration of aromatic molecules into condensed organic matter and inaccessible microsites. To study the rate of PAH sequestration under laboratory conditions, natural sediment samples were spiked with [$^2$H]-PAH and labelled PAH were re-extracted periodically with an aqueous solution of a high molecular weight surfactant (Brij® 700) to estimate not sequestrated PAHs. Adsorbed molecules became slowly sequestered into inaccessible microsites and gradually more difficult to extract. A mathematical model was developed to quantify the rate constants of the sequestration process. The model was based on a three-compartment dynamic system in which aromatic compounds are taken up and sequestered by particulate matter. With the experimental conditions and the knowledge on diffusional process the three-compartment system was simplified to a first-order consecutive-irreversible two-stage reaction. The mean sequestration rate value of $k_2$ was ten times slower than the adsorption rate $k_1$.

*Poster Session*

**Behavior of high molecular weight PAHs in the new sediment layer of the Baie des Ha! Ha! (Saguenay Fjord)**

Émilien Pelletier, Isabelle Desbiens
Institut des Sciences de la Mer de Rimouski, Université du Québec à Rimouski
Rimouski, QC, Canada

ABSTRACT: A series of four sediment cores was collected between 1998 and 2002 in the center of the Baie des Ha! Ha! with the objective to study the behaviour of a number of high molecular weight polyaromatic hydrocarbons (PAHs) deposited immediately after the July 1996 flash flood in the Saguenay Fjord. Dry samples were extracted with dichloromethane (DCM) and then analysed by liquid chromatography (HPLC-Fluorescence). Benzo(a)pyrene (BaP) was selected as the best indicator of the mixing process with the underlying sediment layer. Results show a progressive burying of BaP and its homogenization in the top 0-12 cm layer during the four years of continuous observation. Considering the very low solubility of BaP, its low degradability by micro organisms, and its preferential binding to particulate organic carbon, we consider BaP as a good indicator for the estimation of the organic carbon burying rate in a sediment layer from a recent surface sedimentation.

**Contributions of the Saguenay post-flood project to the design of capping layers**

Hélène Tremblay, Jacques Locat
Département de géologie et de génie géologique, Université Laval, Québec, QC, Canada

ABSTRACT: *In situ* capping of contaminated sediments is a method consisting of placement of a subaqueous layer of sediments, or other material, over contaminated sediments in order to protect the environment from the toxic effects of contaminants. The experience has demonstrated that among possible remediation methods, capping with clean material, employed successfully since the end of the 70's, is one of the most economical and effective approaches. However, there are some lacunas in different aspects of the capping design. During the Saguenay Post-Flood Project, some of them were filled by researchers who have developed methodologies and modelling to improve the capping design. The contribution of the Saguenay Post-Flood Project includes: 1) a methodology to evaluate the bioturbation depth using an axial tomodensitometer; 2) a diagenetic model to evaluate the mobilisation of metals trough the capping layer, 3) a contaminant transfer model that consider bioturbation; 4) a consolidation model that consider bioturbation; 5) a methodology to determine the integrity of the capping layer and the evolution of recolonisation using backscatter data from multibeam sonar surveys, and 6) a decision analysis related to capping design. This paper not only presents these different developments, but also a literature review about these aspects of capping design.