BOTTOM ROUGHNESS CHARACTERISTICS OF THE BAIE DES HA! HA!, SAGUENAY FJORD, QUEBEC, CANADA: A CONSTRAINT ON MAPPING BED THICKNESS OF A NATURAL CAPPING LAYER

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Abstract

Introduction

In July 1996, a major rainstorm in the Saguenay Fjord hinterland and the failure of several earth dams caused extensive flooding and transport of an estimated 9.3 x 10^6 m^3 of sediment to the Baie des Ha! Ha! (Fig. 1; INRS-Eau, 1997). The large influx of sediment resulted in the deposition of a distinctive bed up to 60 cm thick over the entire Baie des Ha! Ha! (Côté et al. 1999). The underlying sediments of the bay contain relatively elevated levels of heavy metal concentrations derived from local sources (Gagnon, 1997), whereas the new bed has much lower levels. As part of a multidisciplinary study to investigate the behaviour of the new bed as a potential capping layer for contaminated sediments, a range of geophysical techniques have been applied to determine the distribution and thickness of the bed in the Baie des Ha! Ha! The objective is to evaluate the different technologies in terms of their capacity to resolve and map the layer. The range of bed thickness, from 0 to 50 cm provides an opportunity to evaluate the real resolving power of penetrative acoustic techniques, including seismic and chirp sonar (Côté, 1999) as well as the potential mapping capacity of seabed reflectivity data from sidescan sonar and multibeam sonar.

In the course of this research, it has become apparent that a major problem in the use of acoustic techniques in the Saguenay Fjord is presented by the predominance of meso-scale bottom roughness (in the order of metres). This roughness appears to be caused by the ubiquity of mass movements along the steep slopes of the fjord. Many of the geochemical and biological results of the larger study of the 1996 layer may be influenced by local seabed conditions, so it is important that the relationships between depositional processes, layer thickness, geotechnical properties and the mesoscale topography be determined. In this light, the objectives of the present paper are: (1) to present the evidence for mass movements and other gravity-driven processes; and (2) to show the effect of meso-scale topography on deposition of the 1996 flood deposit.

Geological Background

The Saguenay Fjord is located on the southern edge of the Canadian Shield and is connected to the St. Lawrence Estuary (Fig. 1). The Baie des Ha! Ha! forms the southerly of two branches of the fjord-head. The typical morphology consists of steep walls and a relatively flat basin floor, extending to depths of 200 m in the distal part of the bay. Most geologic study of the fjord has been concentrated in the northern branch into which the Saguenay River flows. Under normal conditions, the Baie des Ha! Ha! has a relatively low fluvial input with only minor rivers (Rivière à Mars and Rivière des Ha! Ha!) supplying little sediment. During the extreme rainfall event of July 1996, a dam along the Rivière des Ha! Ha! failed and resulted in substantial erosion of the river course and the transport of a large volume of sediments to the Baie des Ha! Ha!

Schafer and Smith (1987) have documented sedimentation rates in the North Arm where it is possible to correlate vertical grain size variation in cores with the discharge record of the Saguenay River. Within this continous sedimentary record, Schafer and Snith (1988) also recognized several discrete sedimentation events that have occurred in historic time, some of which can be directly related to subaerial landslides. The most recent of these events is the 1973 St. Jean Vianney slide that occurred some tens of kilometres inland of the fjord and deposited a layer up to xx cm thick.

Previous studies in the North Arm of the Saguenay have shown that mass movement is a common feature. Syvitski and Schafer (1996) described submarine sliding in the region that was so extensive that they described it as "basin collapse". Large scale features related to sidewall sliding have also been described in the North Arm by Locat et al. (1998) from multibeam sonar data.

Methods

The data presented here were collected in the Baie des Ha! Ha! between June 1997 and October 1998. Sidescan sonar data were collected using a Simrad MS992 dual frequency system. Because of cable limitations, the towfish was deployed near the surface so that only long-range 120 kHz data were recorded. Positioning for these surveys was by differential GPS with a nominal accuracy of $\pm$ 5 m. The sidescan data were mosaiced using Muse-Euterpe software and interpretations were transferred to an Arcview GIS.

High resolution seismic reflection surveys were carried out with an IKB Seistec System characterized by a broad band boomer source and a narrow beam line-and-cone receiver system (Simpkin, 199?). These data were digitally recorded and analysed using Kingdom Suite software from Seismic Micro-Technology Inc.

Sidescan Sonar Interpretation

A set of sidescan sonar mosaics were contructed for the entire Baie des Ha! Ha! arm of the fjord. An example of one mosaic, from the head of the bay is shown in Figure 2. Paper copies of other mosaics are available upon request from the senior author. Four principal types of bottom reflection can be identified (Fig. 3):

(1) **Canyoned southern margin** - Along the southern margin of the fjord, the bottom is characterized by a canyoned surface of very high relief . On the sidescan record, this is recorded as shore-perpendicular zones of very high (black) and very low reflectivity (white), the former representing strong reflections from canyon walls and the latter representing shadow zones behind the ridges that separate individual canyons (Fig. 4). Details of the canyon walls suggest that they have a scalloped morphology, typical of continental slope canyons (Farre et al. 1983). At the boundary with the basin plain, the canyons diverge in smaller distributaries and in some cases form small fans (Fig. 4). This morphology provides clear evidence for the importance of mass movement processes along the southern margin. Sliding in canyon heads probably leads to the development of debris flows and turbidity currents that flow onto the basin plain.

(2) **Cliff-like northern margin** - On the northern margin, the fjord wall does not show a canyon morphology, but is relatively linear (Fig. 5). The cliff-like steepness of the walls is clear from the extensive shadow zone that is observed on slope parallel sidescan images. Immediately below the shadow zone, the seabed has very high reflectivity and shows irregular shore-parallel lineations that are interpreted as bedrock outcroppings. Further below again, the slope shows shore-perpendicular lineations at the limit of the sidescan resolution. These features have a small-scale ridge and gulley morphology, but their interpretation is not clear. One

possible interpretation is that they may represent small individual slope gullies formed by mass movement and turbidity current processes. However, our preferred interpretation is that the lineations are erosional striations formed by the downslope movement of large submarine slides. Similar small-scale lineations have been observed on continental slopes where sliding is observed (Hill, 1983; Piper et al. 1985) and a possible slide mass is imaged downslope of an area of such lineations (Fig. 5).

(3) **Moderate reflectivity basin floor** - A zone of moderate sidescan reflectivity occurs at the base of the margin slopes more or less encircling the basin floor (Fig. 3). To the east, this zone covers the entire basin floor. On sidescan images, the seafloor in this region appears dark grey, mottled and heterogeneous. This is particularly evident in Figure 5 below the zone of shore-perpendicular lineations. A strong amphitheatre-like reflection defines the upper boundary of an identifiable slide mass which corresponds locally to the moderate reflectivity zone (Fig. 5). This strongly suggests that the moderate reflectivity zone is related to slide and slump masses derived from the basin margins and deposited at the periphery of the basin.

(4) **Low reflectivity basin floor** - The central parts of the basins are characterized by relatively low reflectivity, visible in sidescan records as lighter grey tones (Fig. 3). This zone is also characterized by a heterogeneous reflectivity with weak lineations visible in some areas (Fig. 2).

Seismic Data

In traditional stratigraphic terms, high resolution seismic profiles in Baie des Ha! Ha! are very difficult to interpret because of the high relief and lack of lateral continuity within the basin deposits. The typical stratigraphy of the bay consists of thin, discontinuous units of well-stratified sediments interspersed with transparent masses of non-stratified sediment characterized by abundant hyperbolic reflectors (Fig. 6). The two seismic facies pass laterally into each other and no single reflectors can be traced laterally for more than X00 m. This stratigraphy is consistent with the sidescan data indicating that gravitational processes dominate the bay. The transparent masses are interpreted as slump and slide masses which were deposited intermittently in the basin. Most slides resulted in almost complete mixing of the sediments and a loss of coherent internal reflections although some coherent slide masses have been identified (Locat et al. 1998). The thin units of stratified sediments represent periods of more continuous sedimentation between gravitational events. This sediment drapes the slide masses but may be eroded locally by a subsequent slide event.

The surficial parts of seismic records can be compared to the distribution of bottom reflectivity zones 3) and 4). In zones of moderate reflectivity, the seabed is characterized by a mesoscale topography with relief in the order of centimetres to metres and by poor to absent lateral continuity of near-surface reflectors (Fig. 7). Zones of low reflectivity are characterized by smoother seafloor and greater lateral continuity of reflectors in the immediate sub-surface (Fig. 7).

Discussion

The data presented here show that gravitational processes, principally slumping and sliding, but including debris flow and turbidity currents are the dominant processes that have sculpted the seafloor in the Baie des Ha! Ha!. Only small areas of the basin floor, those characterized by low reflectivity, may have escaped the influence of these proceses in very recent times, although evidence for slumping is also present in the sub-bottom of these areas, suggesting that large slump masses have covered the basin at intervals throughout the Holocene.

The implication for studies of the 1996 flood layer are profound. Preliminary results suggest that the bed was itself, at least partly, deposited by gravity processes involving sliding (Crémer et al. 1998) and possibly turbidity current flow (J.-F. Crémer, pers. comm., 1999). Subsequent deposition from suspension under a weak near-bottom current regime was probably also significant. Such processes typically result in a divergent-fill style of sediment accumulation where sedimentation occurs preferentially in topographic lows. Seismic profiles suggets that this kind of sedimentation pattern is typical of the Baie des Ha! Ha!, even on meso-scale topography. Although the 1996 layer has not been unequivocally identified in these records because its thickness approaches the resolution of the seismic system, areas of both moderate and low reflectivity show clear infilling of underlying meso-scale topography (Fig. 7).

Based on the data presented in this paper, we hypothesize that the thickness of the 1996 would be very variable as a result of the meso-scale topography. Greatest bed thickness in the basin areas is likely to occur in meso-scale topographic lows whereas on highs, the thickness would be minimal or the bed may even be absent. To some degree, the distribution of bed thicknesses for the 1996 layer as determined from box cores supports this hypothesis because there is no clear pattern of bed thickness with respect to distance from the mouth of the

Rivière des Ha! Ha! or with water depth (Fig. 8). However, further work will be required at the mesoscale level to determine the exact relationship for the 1996 layer.

This natural meso-scale variability of the bed thickness is potentially problematic for the mapping of the layer using acoustic techniques as the line density required to map at the appropriate scale would be in the order of metres. Furthermore, the bottom return from a rough bottom makes both qualitative recognition and synthetic seismogram modelling of the layer difficult. It is also suggested that the meso-scale roughness of the bed may have an impact on the sedimentological and geotechnical properties of the bed (because of the potentially large variability in depositional conditions and grain size), erodability (because of the hydrodynamic effects of the meso-scale topography on the bottom boundary layer), biological recolonization (because of the inherent heterogeneity of the new seafloor and the hydrodynamic effect on the boundary layer) and consequently on bioturbation, bio-irrigation and geochemical processes. Many of these parameters are presently being studied with the assumption of uniformity or gentle gradients across the bay. A better understanding of seabed heterogeneity will be important for understanding the variability of biological and geochemical processes.

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Figures

1. Location map of the Baie des Ha! Ha!, Saguenay Fjord showing bathymetry and locations of other figures in the paper.
2. Sidescan sonar mosaic of the head of the Baie des Ha! Ha!. Single channel data with a beam direction towards the southwest of data are shown. Grey-scale banding parallel to track lines are due to variations in recording gain levels.

3. Principal bottom types in the Baie des Ha! Ha! based on sidescan sonar imagery.

4. Sidescan mosaic showing detail of submarine canyons on the south side of the Baie des Ha! Ha! Single channel data with a beam direction towards the southwest.

5. Sidescan mosaic showing detail of the cliff-like slope on the northern margin of Baie des Ha! Ha!. Single channel data with a beam direction towards the northwest.

6. Seismic profile showing typical overall stratigraphy and two principal seismic facies described in the text.

7. Seismic profiles showing relationships between meso-scale topography and seabed reflectivity type.

8. Graphs of bed thickness vs distance from R. des Ha! Ha! and vs. water depth.

Figure 2. Sidescan sonar mosaic of the head of the Baie des Ha! Ha!. Single channel data with a beam direction towards the southwest of data are shown. Grey-scale banding parallel to track lines are due to variations in recording gain levels.

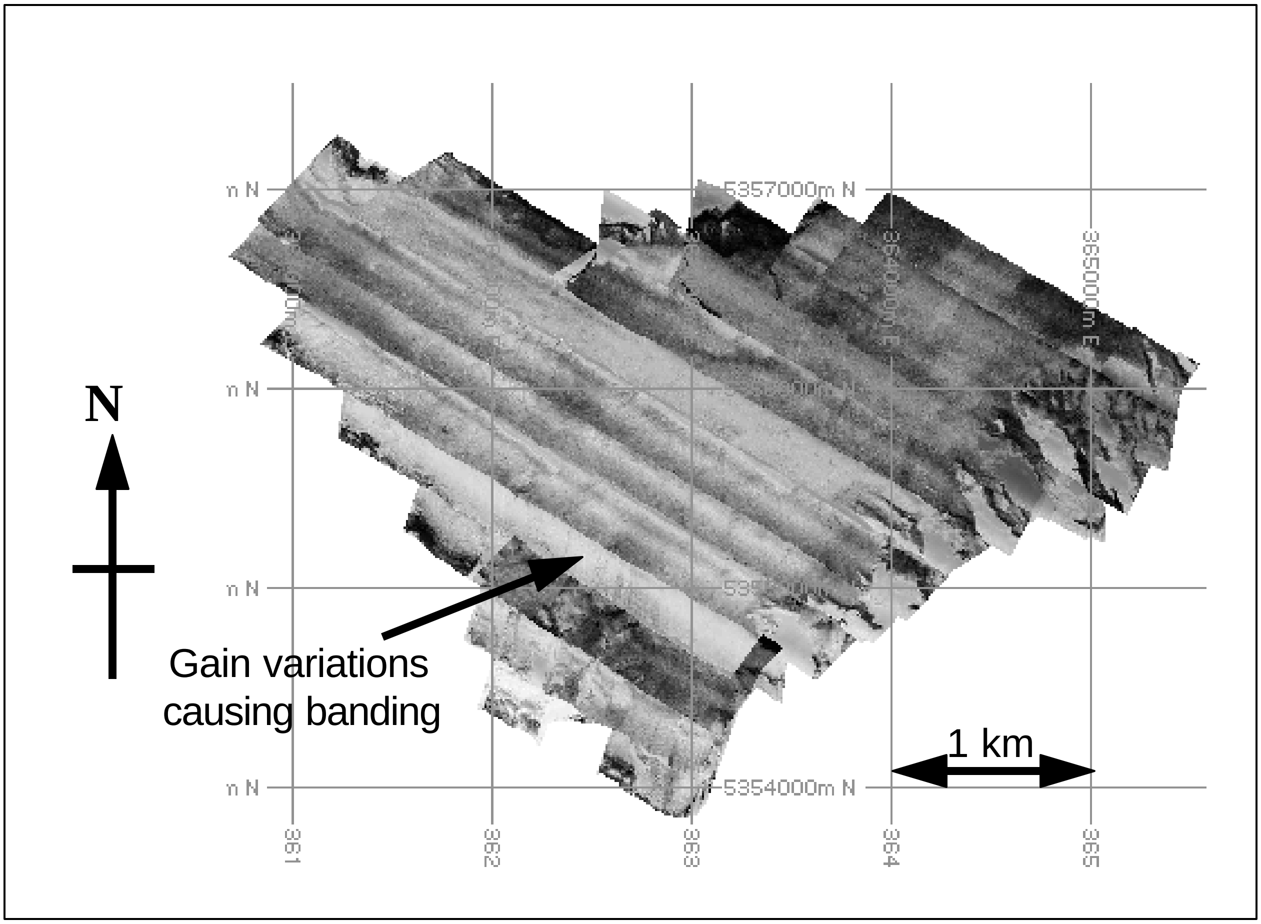

Figure 4. Sidescan mosaic showing detail of submarine canyons on the south side of the Baie des Ha! Ha! Single channel data with a beam direction towards the southwest.

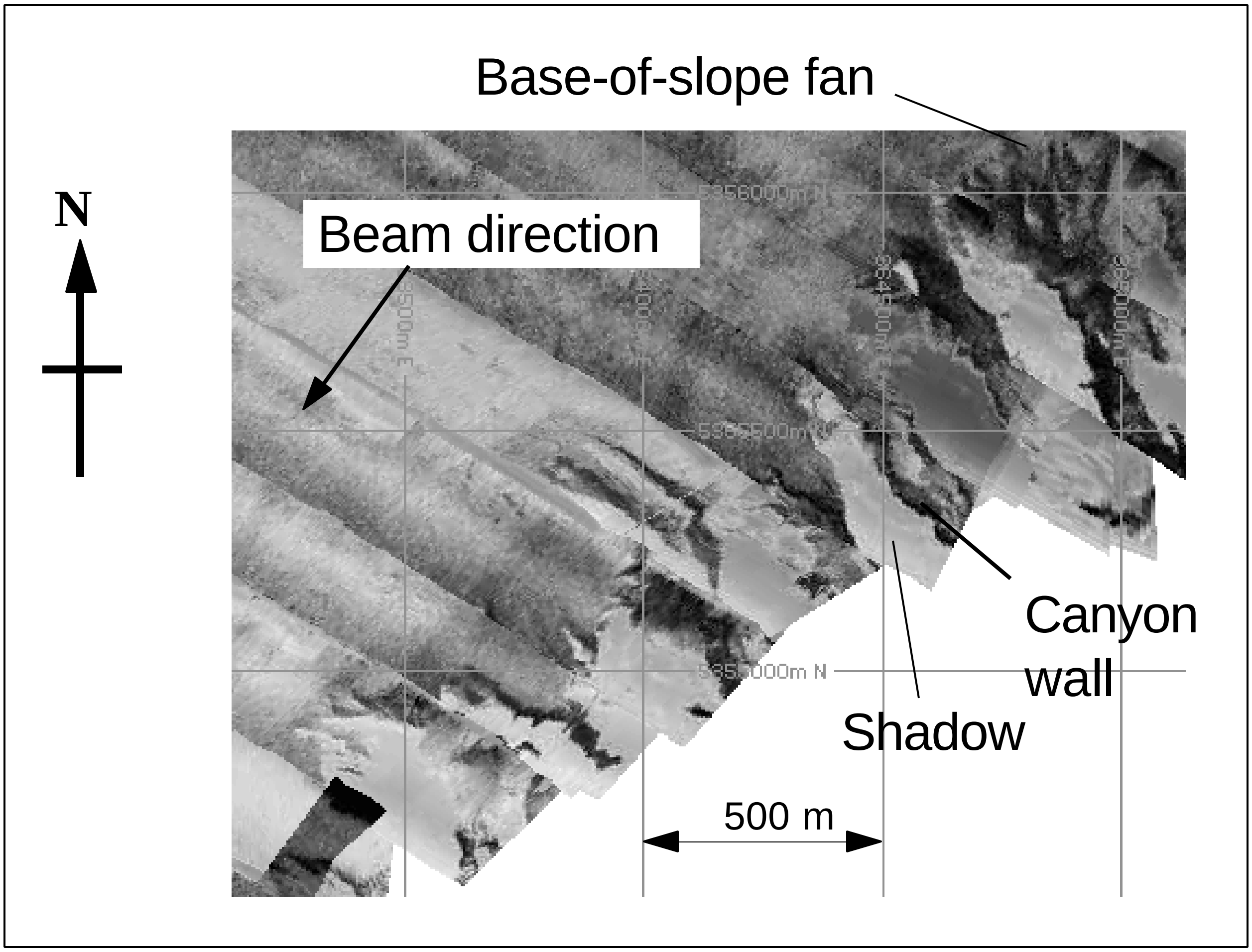

Figure 5. Sidescan mosaic showing detail of the cliff-like slope on the northern margin of Baie des Ha! Ha!. Single channel data with a beam direction towards the northwest.