Seasonally modulated sedimentation in an estuarine depositional regime

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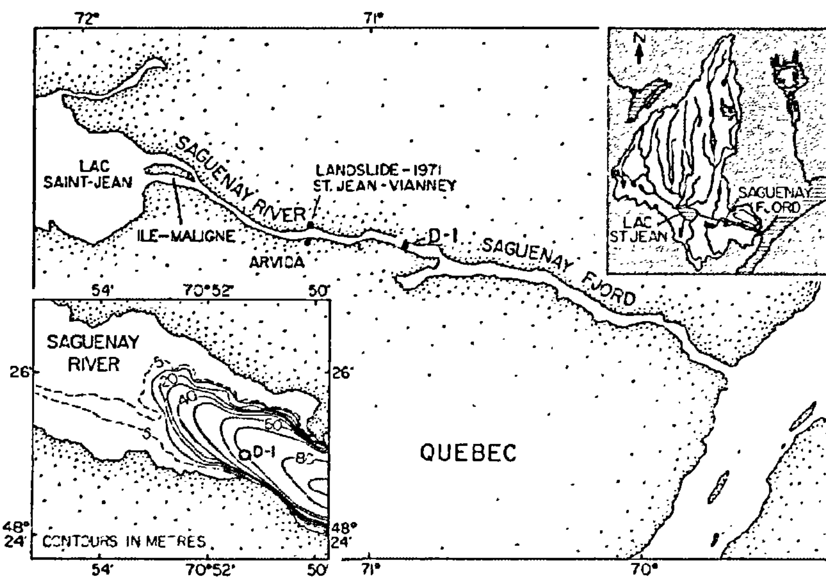
Introduction

One commonly employed assumption used to simplify the modelling of sediment dynamics and the determination of geochronologies in complex, estuarine depositional regimes is that of a constant sedimentation rate. However, in most river-estuarine systems, periodic phenomena, such as the seasonal cycle in river discharge or annual phytoplankton blooms, can produce a seasonal variability in the transport or production of suspended material and a corresponding variation in sedimentation rates in downstream environments. Less predictable "catastrophic" phenomena such as storm events, landslides, etc. can also contribute to seasonally "pulsed" sediment discharge events. Short, periodic "bursts" of high sediment deposition can, in some instances, provide the majority of sediment transport compared to that delivered during the longer intervening quiescent periods of sedimentation. Under these conditions, the mean sediment accumulation rate can be very much different (usually, greater) than the most probable rate. The degree to which a sedimentation regime is skewed from its mean value, ie., the dispersion of its instantaneous rate distribution with respect to its mean sedimentation rate, may have an important effect on other environmental variables such as the composition and activity of benthic community assemblages, the rates of sediment diagenesis and the efficiency of particle and contaminant transport from the water column to the sediments.

The annual variability in estuarine sedimentation rates could be determined synoptically using sediment traps. However, this method will provide only the most recent record and will invariably reflect contemporary climatological and hydrological conditions. An alternative method, employed in the present study in the Saguenay Fjord, Quebec, utilises the sequence of variations in sedimentation rate recorded in the sediments in the form of textural varves or particle size unconformities. This type of analysis can be carried out in estuarine systems having a bi-modal depositional mechanism in which pulsed inputs of coarser-grained sands and silts during high Spring river discharge conditions are superimposed on the ambient sedimentation of finer-grained clays and organic material. In the present case, the quantity of sediment pulsed into the system is estimated by the extent of dilution of the ^{210}Pb signal, assuming that ^{210}Pb transport can be simulated using a Constant Flux (CF) technique. The applicability of the CF technique to the Saguenay Fjord sediment regime is validated using time-stratigraphic horizons associated with landslide events and the thresholds for anthropogenic contaminant loadings. The purpose of this study is to evaluate the historical importance of sediment deposition during high energy, Spring river discharge conditions compared to ambient sedimentation patterns that prevail during the remainder of the year.

Methods and environmental setting

The Saguenay Fjord is a deep (250 m) glaciated valley carved into the crystalline rocks of the Canadian Shield, located 300 km Northeast of Montreal, Quebec (Figure 1). Sedimentation rates in the fine-grained clayey sediments covering the bottom of the fjord decrease exponentially with increasing distance from the mouth of the Saguenay River. The highest sedimentation rates (> 4 $g.cm^2.yr^1$; Smith and Ellis, 1982) occur at the head of the fjord where an abrupt decrease in river water velocity caused by the widening and deepening of the river channel as it enters the fjord promotes the rapid deposition of suspended material and bedload. Further, a high flux of terrigeneous organic matter derived from upstream pulp and paper mills and sawmills located near Arvida (Figure 1) has produced an extremely anoxic benthic environment, almost totally devoid of bioturbating organisms. This unique combination of high sedimentation rate and the absence of sediment mixing has resulted in well-preserved sediments containing an excellent record of chronological events during the past 100 years.



I Figure 1
Sediment cores D-1, 007 and C-7 were collected from Station D-1 in the Saguenay Fjord in 1979, 1982 and 1997, respectively.

Two depositional events have had a pronounced impact on sediment accumulation rates in the Saguenay Fjord. In 1971, a landslide at Saint-Jean Vianney (Figure 1) resulted in the displacement of 25 million tonnes of ancient marine clays into the Saguenay River and produced a distinct 1971 clayey horizon distinguishable by abrupt changes in texture, colour and geochemical profiles in all sediment cores in the upper arm of the fjord (Smith and Walton, 1980; Schafer and Smith, 1987). Massive flooding in the Saguenay region in 1996 produced a second, clayey time-stratigraphic horizon in more recently collected cores from the fjord.

A 2 metre, Lehigh gravity core (10 cm I.D.) was collected at Station D-1 in the upper arm of the fjord (Figure 1) in 1979. This core was X-radiographed, subsampled at 1 cm intervals and analysed for a range of geochemical properties and contaminants at one cm intervals, including the radionuclide tracers, ^{137}Cs, $^{239,240}Pu$, ^{226}Ra and ^{210}Pb using alpha and gamma spectrometric methods outlined in Smith *et al.* (1987). Organic matter, porosity and particle size measurements were also carried out using methods outlined in Smith and Schafer (1987). The station was re-occupied in 1982 and 1997 when a piston core (core C-7) and another Lehigh gravity core (core 007), respectively, were collected.

Previous studies in the upper arm of the Saguenay Fjord have indicated that, despite the seasonal modulation of the ^{210}Pb signal, the annual flux of ^{210}Pb remains relatively constant. This is due to the fact that the enhanced inputs of sands and silts during the Spring river discharge carry comparatively little additional excess ^{210}Pb owing to their inefficient scavenging of this particle-reactive tracer from the water column. As a result, it has been shown (Smith *et al.*, 1987) that it is feasible to apply a Constant Flux (CF) ^{210}Pb technique (Robbins, 1978) to the interpretation of the experimental results. The geochronology for a core is then given by;

$$T = \frac{1}{\lambda} \ln(1 - I(m) / I^{\circ})^{-1} \qquad 1$$

where, T is the time, λ is the radioactive decay constant for ^{210}Pb (0.0311 y^{-1}), I(m) is the inventory of excess ^{210}Pb above a sediment depth, m and I^{∞} is the total inventory of ^{210}Pb in the sediments. The sediment accumulation rate, w, is given by;

$$\omega = \frac{\lambda}{A} (I^{\circ} - I(m)) \qquad 2$$

where, A is the ^{210}Pb activity at a depth, m. The time-invariant ^{210}Pb flux for the CF technique is;

$$F = I^{\circ} / \lambda \qquad 3$$

As noted by Robbins *et al.* (2000), the CF technique is actually a mapping method and not a model, because it simply uses an algorithm to convert excess ^{210}Pb activities into dates and sediment accumulation rates and has no predictive value.

Results

The ^{210}Pb sediment-depth distributions for the three sediment cores are illustrated in Figure 2. The impact of the 1971 St. Jean Vianney landslide is defined by a depositional unconformity of grey clay having reduced ^{210}Pb activities in each core. The bottom of this layer was located at depths of approximately 40 cm, 55 cm and 165 cm in 1979, 1982 and 1997, respectively corresponding to a mean sedimentation rate of about 6 cm.yr^{1} at this location. The 1996 flood event has produced a similar, ^{210}Pb -deficient unconformity near the top of core 007 (collected in 1997). The peaks and troughs in ^{210}Pb distributions (apart from the landslide/flood layers) reflect seasonally-modulated inputs of coarser-grained silts and sands during the spring river discharge of each year, characterised by reduced ^{210}Pb levels, alternating with the ambient deposition of finer-grained clays and organic matter having higher concentrations of ^{210}Pb.

The total ^{210}Pb inventory, I°, and inventories above a given depth m, I(m), were measured through cores D-1 and 007. These results were then used to determine the core geochronology, sediment accumulation rates and the ^{210}Pb flux from equations 1, 2 and 3, respectively. The values of ω for each core are plotted as a function of T in Figure 3. The entire inventory of excess ^{210}Pb is not contained in the upper 260 cm of core C-7, and an alternative method must be employed in order to estimate I°. Since the 1971 landslide event is pronounced and easily defined, then this time-stratigraphic horizon was used to calculate I° from Equation 1. This value of I° was then used in equations 2 and 3 to calculate the core geochronology.

Obviously, any geochronology determined using the CF technique must be validated using independent time-stratigraphic horizons (Robbins and Edgington, 1975), because there is no external con-

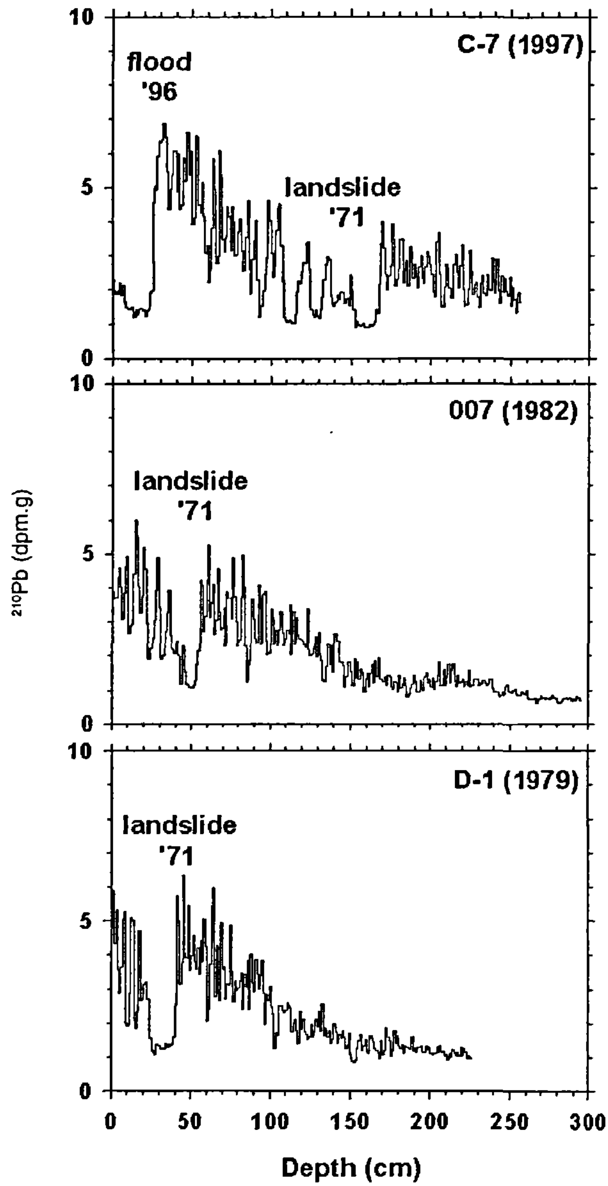
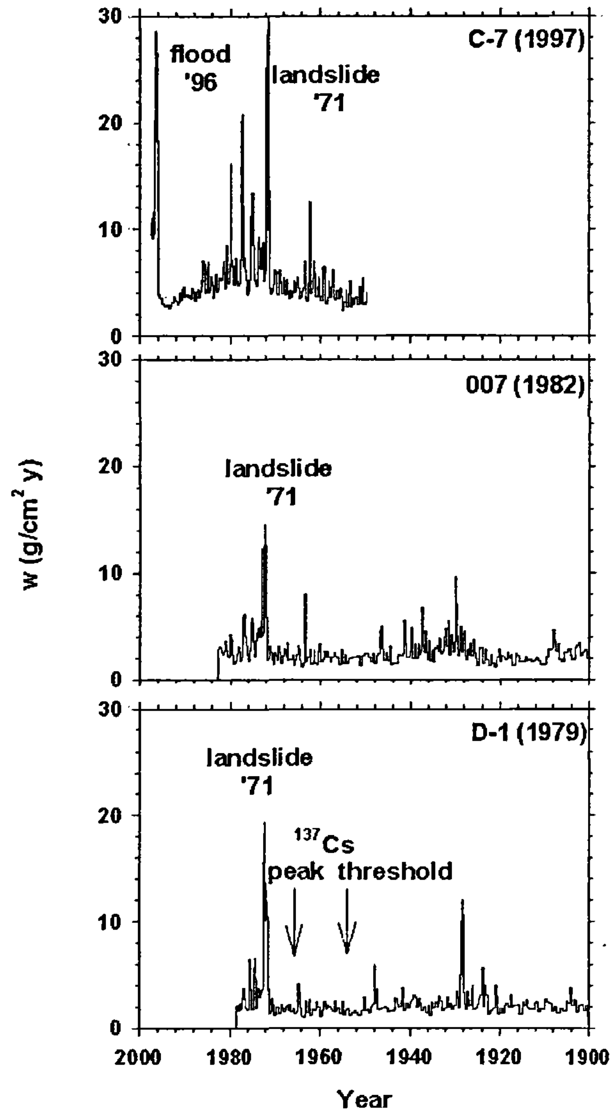


Figure 2
^{210}Pb sediment-depth distributions for the three cores,
D-1 (collected in 1979), 007 (1982) and C-7 (1979)
were measured at 1 cm intervals for the entire length of each core.

straint imposed on the data, ie. each ^{210}Pb data point is equally valid regardless of its actual value. For cores D-1 and 007, the agreement of the landslide horizon with a date of 1971 is sufficient validation for the CF technique. However, an alternative horizon must be employed for core C-7, because the 1971 horizon was used to estimate the ^{210}Pb flux, itself. Numerous geochemical and textural horizons have been identified in each of these cores, but a series of horizons common to all are those associated with the deposition and transport of fallout radionuclides. Specifically, the initial introduction of measurable levels of ^{137}Cs in 1954 and the maximum ^{137}Cs flux to the sediments in 1964 provide geochemical markers whose positions in each core are in good agreement with calculated geochronologies (Figure 3). This independent validation of the CF results provides some assurance that the ensemble of sediment accumulation rates shown in Figure 3 for each core bear some semblance to reality. In fact, there are numerous additional horizons that have also been used to validate the geochronologies for these cores including; (1) a 1947 Hg horizon associated with the construction of a chlor-alkali plant at Arvida (Smith and Loring, 1981; Smith and Schafer, 1999); (2) a 1924 clay landslide horizon associated with a landslide at Kenogami (Smith and Schafer, 1987), and; (3) a 1910 organic matter horizon resulting from the beginning of the pulp and paper industry in the Saguenay region (Smith and Schafer, 1987).

The results from these three cores show that the 1971 landslide unconformity has survived intact and continues to provide an important time-stratigraphic horizon in Saguenay Fjord sediments. It was joined by a second, flood-produced unconformity in 1996 and, together, the two horizons can produce geochronological reference points throughout the fjord sediments. This time series of sediment cores also shows that the history of seasonally modulated maxima in ^{210}Pb sedimentation rates are preserved over relatively long periods. Sedimentation rate maxima and minima can be cross-correlated between the sediment cores and can be related to the history of river discharge (Smith and Schafer, 1987). The ultimate goal of this study is to use the record of river discharge events preserved in the sediments of the fjord to resolve the history of river discharge during the 18^{th} and 19^{th} centuries and thereby provide new insights into the history of temperature, precipitation and climate change in Eastern Canada.



I Figure 3

Sediment accumulation rates, w ($g.cm^{-2}.yr^{-1}$) were calculated from the ^{210}Pb distributions using a constant flux technique and equations 1,2 and 3 given in the text. The geochronologies for each core were validated using horizons associated with the initial appearance of fallout ^{137}Cs (1954) and the maximum flux of fallout ^{137}Cs (1964). The 1971 landslide and 1996 flood event horizons are also in agreement with the ^{210}Pb constant flux geochronologies.

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