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Isotopic constraints of sedimentary inputs and organic carbon burial rates in the Saguenay Fjord, Quebec

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The Saguenay Fjord (Quebec) has exceptionally high sedimentation rates resulting in up to 100 m-thick Holocene sequences filling some of its basins, partly due the frequent occurrence of rapidly deposited layers (landslides, seismic events, floods). In the present study, special attention is paid on the incidence of such events on organic carbon (OC) fluxes, sources and burial rates, using physical, sedimentological, geochemical and isotopic measurements on 4 sediment cores raised from the inner basin of the fjord and the adjacent Baie des Ha!Ha! In these cores, rapidly deposited layers (RDL) include notably a turbidite linked to a major earthquake in 1663, a landslide layer dating from 1971 (Saint-Jean-Vianney landslide), and a flood layer from 1996. Compared with background sediments, RDL are characterized by low OC contents (<1%), relatively high $CaCO_3$ contents (>2%), and low $\delta^{13}C$ values in OC (<−27‰). These geochemical properties indicate incorporation of reworked marine sediments from the Laflamme Sea, which occupied the area during postglacial times. $\delta^{13}C$-OC values (−26.8 ± 0.2‰) and C/N ratios (17.7 ± 1.7) in the pre-industrial, pre-1663 fjord sediments, indicate that most sedimentary organic matter (OM) was then of terrigenous origin. Paper mill activity during the 20th century has resulted in OM fluxes growing almost exponentially until the mid-1960s, when major changes in industrial practices and the implementation of environmental regulations during the 1970s and later on, reduced the amount of industrial OM discharged into the fjord. This industrial OM shows an isotopic signature of −26.34 ± 0.02‰ and C/N ratios >20, not unlike those of the regional terrestrial OM. OC burial rates since the 1663 earthquake varied between ~20 and 290 $gC\ m^{-2}\ yr^{-1}$. RDL seem to favour OC preservation in the fjord by reducing bioturbation and both oxic and anoxic OC degradation, and by contributing themselves to higher carbon burial rates. Therefore, transitional environments such as the Saguenay Fjord could represent significant long-term carbon sinks.

Keywords: $\delta^{13}C_{org}$; Organic carbon; Burial rates; Turbidite; Saguenay Fjord; $\delta^{15}N$

Organic carbon (OC) storage on continental margins represents a significant component of the carbon cycle (Walsh et al., 1981; Walsh, 1991; Bauer and Druffel, 1998). Information on OC sources, fluxes and storage rates along these margins is thus needed to constrain the size and residence time of this OC reservoir. Several recent studies have examined this issue on the long and highly productive margins of eastern Canada (e.g. Colombo et al., 1995; Muzuka and Hillaire-Marcel, 1999; Mucci et al., 2000; Silverberg et al., 2000). These studies suggest that most of the OC deposited in the Gulf of St. Lawrence and

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along the southeastern Canadian margin has a marine origin.

The above studies do not explain the fate of terrestrial particulate OC that is produced in the boreal forest domain of eastern Canada and is ultimately transported by rivers into the Gulf of St. Lawrence. Muzuka and Hillaire-Marcel (1999) concluded that this terrestrial particulate OC was trapped in the estuarine environment. However, precise estimates for OC burial rates in such environments are still poorly constrained and/or almost exclusively restricted to the Laurentian Trough area (de Vernal et al., 1991; Lucotte et al., 1991; Louchouarn et al., 1997a; Silverberg et al., 2000).

From this view point, the Saguenay Fjord (Fig. 1) presents many interesting features, most notably its exceptionally high sedimentation rates (up to a few cm/year; Smith and Walton, 1980). These have resulted in very thick Holocene sequences, as much as hundred meters, in the inner basin of the fjord (see Syvitski and Praeg, 1989). Moreover, both very high sedimentation rates and relatively high OC content of the sediment imply that this fjord is a prominent storage site for terrestrial particulate OC (e.g. Tan and Strain, 1979; Pocklington and Leonard, 1979; Louchouarn et al., 1999).

The present study specifically addresses this issue by using physical, sedimentological, geochemical and isotopic analyses of four cores raised during a cruise of the CSS Martha L. Black (97-01). Earlier studies already provide some constraints on the sources of the OC being deposited in the fjord and seawards: for example, carbon/nitrogen ratios (C/N) and C and N isotopic compositions have shown that the organic matter (OM) is primarily of terrigenous origin in the fjord, and that the terrigenous fraction rapidly decreases seawards in relation to marine OM (Pocklington, 1976; Tan and Strain, 1979; Pocklington and Leonard, 1979; Muzuka and Hillaire-Marcel, 1999; Louchouarn et al., 1999). However, precise data concerning OC sources as well as long term OC burial rates in the fjord are not available, as earlier studies tended to study only grab or box-core samples.

Furthermore, sedimentary sequences in the fjord are characterized by numerous rapidly deposited layers (RDL), which have been linked to seismic events, floods and landslides. Indeed, during the last 350 years, the Saguenay Fjord region has been struck by several natural disasters. These include at least five major earthquakes (≥6 on the Richter's scale; Smith, 1962; Basham et al., 1985), two landslides (Schafer and Smith, 1988) triggered from the marine terraces of the postglacial Laflamme Sea (Lasalle and Tremblay, 1978), those of Kénogami (1924) and Saint-Jean-Vianney (1971), and finally, floods, such as that of the summer of 1996, which swept more than 15×10^6 m^3 of sediments into the Saguenay Fjord (Lapointe et al., 1998). The incidence of such RDL on OC preservation and storage rates also needs to be documented.

The Saguenay Fjord is a long (90 km) and narrow (1–6 km) submerged valley (Fig. 1). The inner basin, east of Saint-Fulgence, is the largest and deepest one. The Saguenay Fjord is part of the large Saguenay-Lac-Saint-Jean watershed (85 500 km^2; Fortin and Pelletier, 1995) and occupies an ancient tectonic depression in the Precambrian rocks of the Canadian Shield (Drainville, 1968). It has been deepened by the advance and retreat of the Late Quaternary glaciers. Following the regional ice retreat about 10 000 ^{14}C years ago, and due to glacio-isostatic depression, the saline waters of the Laflamme Sea submerged the area up to 198 m above modern relative sea level (Lasalle and Tremblay, 1978). They deposited slightly carbonated clays (Lasalle and Tremblay, 1978), often referred to as 'quick clays' (Locat et al., 1984) due to the frequent occurrence of landslides along the Laflamme Sea marine terraces.

Two well-stratified water masses separated by a sharp pycnocline are present in the Saguenay Fjord. The shallow surface layer (0–10 m) is composed of brackish waters (0–10 of salinity) and flows seawards. The temperature of this layer, which freezes in winter, rises up to 16°C in summer. The deep layer (>10 m) is composed of the penetrating landward waters of the Lower Estuary. The deep layer has a stable salinity of about 30.5 (Syvitski and Schafer, 1996) and shows seasonal temperature variations between 0.4 and 1.7°C (Fortin and Pelletier, 1995).

High-resolution seismic reflection profiles reveal the presence of a thick Quaternary sequence filling the fjord (Syvitski and Praeg, 1989; Praeg and

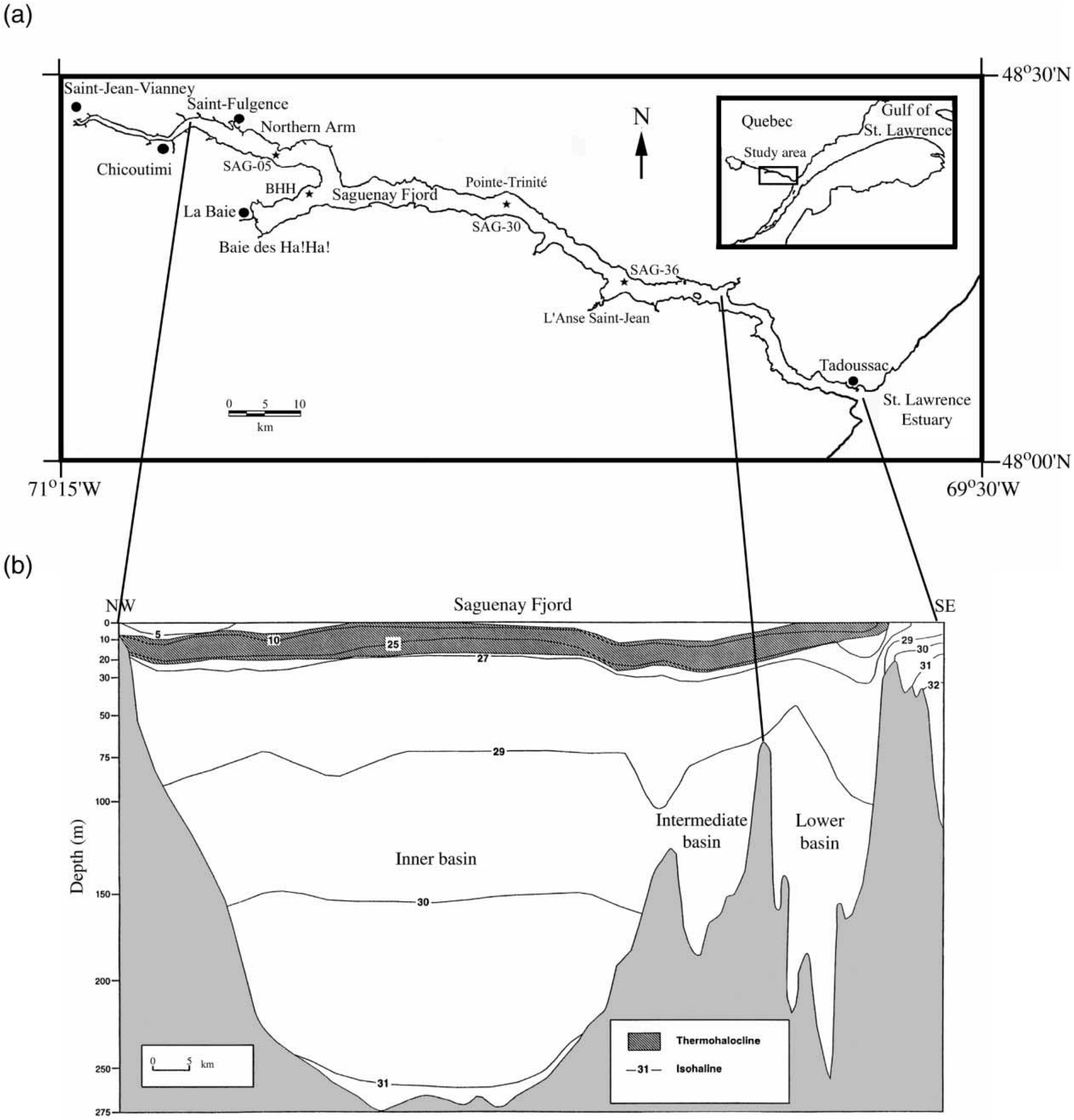

Fig. 1. The Saguenay Fjord (Quebec). (a) Location of sampling sites. (b) Longitudinal transect along the Saguenay Fjord showing the bottom morphology and salinity gradients.

Syvitski, 1991), averaging 800 m in thickness, but reaching up to 1300 m thick in the intermediate basin. Postglacial Holocene sediments account for at least 100 m in the thickest part of the sequence (Syvitski and Praeg, 1989; Praeg and Syvitski, 1991). A widely distributed sedimentary unit near the top of the Holocene sequence was deposited during a major seismic event in 1663, reaching up

Table 1
Cores used in this study

Core	Site location	Name used in this study	Latitude	Longitude	Water depth (m)
MB97-01-01TWC04	Northern Arm	SAG-05	48°24.75′N	70°49.85′W	85
MB97-01-17PC09	Baie des Ha!Ha!	BHH	48°22.00′N	70°46.29′W	165
MB97-01-12TWC12	Pointe Trinité	SAG-30	48°21.77′N	70°23.72′W	270
MB97-01-14PC13	Anse Saint-Jean	SAG-36	48°15.72′N	70°09.75′W	241
MB97-01-14BC07	Anse Saint-Jean	Box core SAG-36	48°15.72′N	70°09.77′W	242

to 16 m in thickness in the deepest part of the inner basin (Syvitski and Schafer, 1996; Hillaire-Marcel and Turon, 1999). Recent sedimentation rates decrease from 7 cm yr^{-1} near Saint-Fulgence to less than 0.1 cm yr^{-1} in the deepest part of the inner basin (Smith and Walton, 1980; Perret, 1994; Zhang, 2000).

3.1. Coring sites

We studied four cores raised during the 1997 cruise of the CSS *Martha L. Black* (97-01; Table 1; Fig. 1). These include one trigger weight core (TWC) raised from the Northern Arm of the fjord at site SAG-05, one piston core (PC) raised from the Baie des Ha!Ha!, a second TWC raised from site SAG-30 near Pointe Trinité and a second PC raised from site SAG-36 near Anse-Saint-Jean (Table 1; Fig. 1). On land Laflamme Sea sediments from the 1971 Saint-Jean-Vianney landslide location (SJV-1 and SJV-2; Table 3) were also collected for carbon content and isotopic measurements. Partial loss of sediment has occurred at the top of each core. However, based on visual correlation of the layer assigned to the 1996 flood between box-cored sequences and the corresponding long cores listed here, it was determined that the missing interval rarely exceeds a few centimeters (unpublished data).

3.2. Core processing

Each core was described with respect to texture, colour and sedimentary structures. Wet bulk density and magnetic susceptibility were determined using a GEOTEK™ multisensor track instrument (MST). Colour reflectance measurements were performed on three cores, BHH, SAG-30 and SAG-36 using a Minolta™ hand-held spectrophotometer and have been expressed using grey scale values, ranging from 0 (absolute black) to 100 (absolute white). Water content was calculated by comparative weighting of wet and dry sediment samples. Grain size analyses were performed on bulk sediments at the Laboratoire de Géologie des Chaînes Alpines at Université de Savoie, using a Malvern™ 'Master sizer S' laser diffraction grain size analyzer.

3.3. Geochemical and isotopic analyses

Organic carbon (OC), nitrogen (N) and inorganic carbon (IC) content were measured with a Carlo-Erba™ elemental analyzer according to the following method. A first aliquot was dried, ground and analyzed for its total carbon (TC) and total nitrogen (TN) content. A second aliquot was acidified twice with HCl (1N) to dissolve carbonates, and then washed and analyzed for its N and residual C content which is considered to exclusively represent OC. Inorganic carbon was then calculated by balancing the difference between the two measurements. OC and N contents are expressed in dry weight percent of total sediment and represent the mean of 2 analyses. Uncertainties ($\pm 1\sigma$), as determined from replicate measurements of standard materials, average ±5% (relative) for OC and N contents.

The above method may result in biases for IC calculations when HCl (1N) hydrolysable minerals other than carbonates are present in the sediment (e.g. Rainswell et al., 1994; Leventhal and Taylor, 1990). Therefore, we decided to duplicate some IC determinations based on direct coulometric measurements. In two cases (cores SAG-30 and SAG-36), the two methods yielded identical IC values within uncertainties; however, in samples from cores SAG-05 and

Table 2
Sedimentation rates reported at the study sites (generally based on analyses of distinct cores collected during several cruises)

Core	Sedimentation rate (cm yr^{-1})	Reference and method
SAG-05	1.5	This study; marker horizons
	0.9	Barbeau et al. (1981); ^{137}Cs
	0.8	Savard (2000); ^{210}Pb
	0.7	Savard (2000); ^{137}Cs
	0.5	Smith and Walton (1980); ^{210}Pb
Baie des Ha!Ha!	0.2	This study; marker horizons
	0.2	Barbeau et al. (1981); ^{137}Cs
SAG-30	0.2	St-Onge et al. (1999); marker horizons
	0.35	Zhang (2000); ^{210}Pb
	0.29	Zhang (2000); ^{137}Cs
	0.23	Smith and Walton (1980); ^{210}Pb
	0.25	Barbeau et al. (1981); ^{137}Cs
SAG-36	0.24	This study; ^{210}Pb
	0.36	This study; marker horizons

BHH, the two methods yielded significantly different results. This indicates the presence of HCl-hydrolysable minerals in the sediment of the latter set of cores. Hence, OC contents for these cores were determined using the difference between the TC measurements (from elemental analysis) and IC content from coulometric measurements. IC content for all cores is expressed as $CaCO_3$ equivalent in dry weight percent of total sediment. Henceforth, C/N atomic ratios represent OC to total N ratios.

Two methods were used for stable isotope measurements: a manual extraction line for the recovery of N_2 and CO_2 for isotopic measurements in core SAG-30 and an automatic extraction system coupled to a mass spectrometer for $\delta^{13}C$ measurements for all other cores. In the first case, the procedure was done according to Macko (1981). Acidified aliquots were combusted in the presence of cupric oxide wire and high quality granular copper in a quartz tube for 1 h at 850°C. The evolved N_2 and CO_2 were dehydrated and subsequently analyzed on a VG-PRISM™ mass spectrometer for ^{13}C and ^{15}N content. Isotopic data are reported in δ values (‰) with reference to V-PDB (Coplen-Tyler, 1995) and atmospheric N_2 (Mariotti, 1983), respectively, following the usual corrections (e.g. Craig, 1957). Overall analytical uncertainties ($\pm 1\sigma$) for this method, as determined from routine replicate measurements using standards, are better than ± 0.1‰ for both isotopes. For the second procedure, dried, ground and acidified aliquots were loaded on the carousel of a Carlo-Erba™ elemental analyzer in-line with a Micromass IsoPrime™ instrument, and sequentially run for ^{13}C content. Here, overall analytical uncertainty ($\pm 1\sigma$), also determined from replicate measurements of standards, is ± 0.15‰.

The lead-210 measurements on sediment samples from box core SAG-36 were made after chemical treatment, purification and deposition on a silver disk following routine procedures at GEOTOP (e.g. Courcelles, 1998) by alpha counting of the daughter ^{210}Po. In order to insure secular equilibrium between ^{210}Pb and ^{210}Po in the sediment samples, these measurements were performed one year after the box core had been collected.

4.1. Lithostratigraphy and regional correlations

Core SAG-05, from the Northern Arm of the Saguenay Fjord (Fig. 1), consists mainly of bioturbated, dark grey clayey silts, relatively rich in organic carbon (Fig. 2) with two distinct layers. The first one, between 53 and 45 cm, is a light grey clayey layer already described by various researchers and assigned to the 1971 Saint-Jean-Vianney landslide (Smith and Walton, 1980; Schafer and Smith, 1987; Smith and Schafer, 1987; Schafer and Smith, 1988; Locat and Leroueil, 1988). The second distinctive layer is found between 8 and 0 cm. It consists of light grey

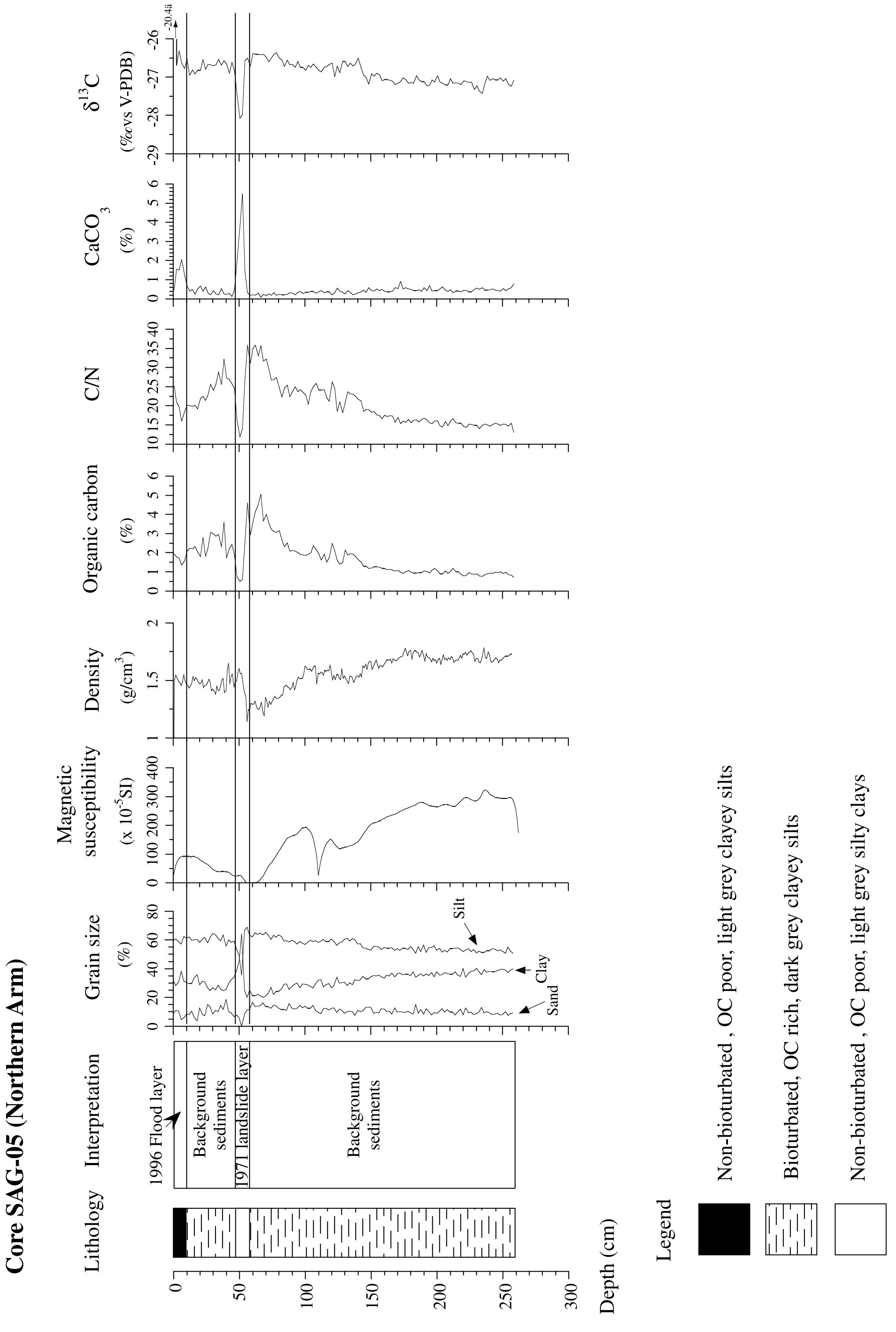

Fig. 2. Core SAG-05 (Northern Arm of the Saguenay Fjord). Lithology, core interpretation, physical, geochemical and isotopic properties. Two rapidly deposited layers are observed in this core and are assigned to the 1971 Saint-Jean-Vianney landslide and to a 1996 flood, respectively.

clayey silts deposited during the 1996 flood. Based on the age of these two rapidly deposited layers (RDL), a sedimentation rate of $\sim 1.5\ \mathrm{cm\ yr^{-1}}$ is estimated at this site with RDL being excluded from the calculation (i.e. under steady-state sedimentary conditions). This value is slightly greater than those based on ^{210}Pb and ^{137}Cs measurements (averaging $\sim 1\ \mathrm{cm\ yr^{-1}}$) reported for other cores collected in the vicinity (Smith and Walton, 1980; Barbeau et al., 1981; Savard, 2000; Zhang, 2000; Table 2). However, our estimate (i.e. $1.5\ \mathrm{cm\ yr^{-1}}$) seems supported by independent information from a box core sampled at SAG-05, in 1994, by Louchouarn and Lucotte (1998). In this core, the 1971 RDL was found at a depth of 30 cm. Based on this chronostratigraphic marker position and assuming steady-state sedimentary conditions, one may calculate a mean sedimentation rate of $1.3\ \mathrm{cm\ yr^{-1}}$. Differences in sedimentation rates calculated from distinct cores are to be expected when coring at a site such as SAG-05, due to its shallowness and high energy sedimentary dynamics. In addition, the use of distinct coring devices is also likely to result in differences in apparent sedimentation rates.

The core from Baie des Ha!Ha! contains a complex series of silty clay to clayey silt layers representing ‘normal’ sedimentary conditions (hereinafter referred to as background sediments), alternating with turbidite and debris flow units (Fig. 3). At the base of the core (623–484 cm) a series of sharp-based turbidites with oblique and cross-laminated layers and frequent sharp erosional contacts are found. The uppermost turbidite of this layer is separated from the underlying unit by a sharp contact and has a sandy base grading upwards into more homogeneous light grey silty clays. Unlike the underlying turbidites, it is characterized by a finer grain size distribution and low magnetic susceptibility, low density, low $CaCO_3$ contents and relatively high OC (Fig. 3). Overlying this turbidite layer is a debris flow unit consisting of soft mud clasts within a silty to sandy matrix and having elevated magnetic susceptibility, density and $CaCO_3$ concentration (Fig. 3). No historical event that corresponds to this bottom turbidite–debris flow sequence has been found in the available literature. A dark grey, strongly bioturbated, OC-rich clayey silt layer (282–103 cm) overlies this sequence and contains three thin sandy beds rich in organic debris (leaves, roots and wood fragments), which may account for the high OC contents measured at 270, 238 and 220 cm (Fig. 3). A light grey turbidite (103–74 cm) low in OC and high in $CaCO_3$ contents overlies this layer (Fig. 3). A dark grey, OC-rich, bioturbated silty clay layer (74–10 cm) and a light grey clayey-silt layer between 10 cm and the surface complete the sedimentary sequence of this core. The latter is a RDL linked to the 1996 flood.

The dark grey clayey silts between 282 and 103 cm imply background sediments (except for the sandy beds), and that turbidites found above and below it in the sedimentary sequence must correspond to two distinct sedimentological events. Syvitski and Schafer (1996) described a similar sequence in a nearby core from Baie des Ha!Ha! Based on its texture, colour and sedimentological properties, the upper turbidite from this site is correlated with the RDL assigned to the 1663 earthquake, as defined by Schafer and Smith (1987), Perret et al. (1995) and St-Onge et al. (1999). Using the 1996 and 1663 RDL as chronological benchmarks, a sedimentation rate corresponding to $0.2\ \mathrm{cm\ yr^{-1}}$ is inferred for steady-state conditions at this site (i.e. RDL excluded), which is in good agreement with that of $0.2\ \mathrm{cm\ yr^{-1}}$ determined by Barbeau et al. (1981) for the area (Table 2).

Core SAG-30, from the deep inner basin of the fjord (Fig. 1), contains two major sedimentary units. The base (200–70 cm) is a very homogeneous grey silty clay layer, poor in OC, but having more $CaCO_3$ than the overlying sediments (Fig. 4), that is correlated to the top of the turbidite triggered by the 1663 earthquake (St-Onge et al., 1999; see also Perret et al., 1995; Schafer and Smith, 1987). The upper section of the core (70–0 cm), is composed of dark grey, OC-rich, bioturbated clayey silts to silty clays and characterizes background sediments (Syvitski and Schafer, 1996). Based on the downcore depth of the 1663 RDL, a $0.2\ \mathrm{cm\ yr^{-1}}$ sedimentation rate is estimated for this site under steady-state conditions (see also St-Onge et al., 1999), which is in good agreement with sedimentation rates previously reported for the inner basin (Smith and Walton, 1980; Barbeau et al., 1981; Zhang, 2000; Table 2).

Core SAG-36, recovered on the eastern floor of the inner basin of the fjord, near Anse Saint-Jean (Fig. 1), contains three major units. The basal unit (661–296 cm) consists of dark grey, slightly bioturbated, homogeneous clayey silts to sandy muds with

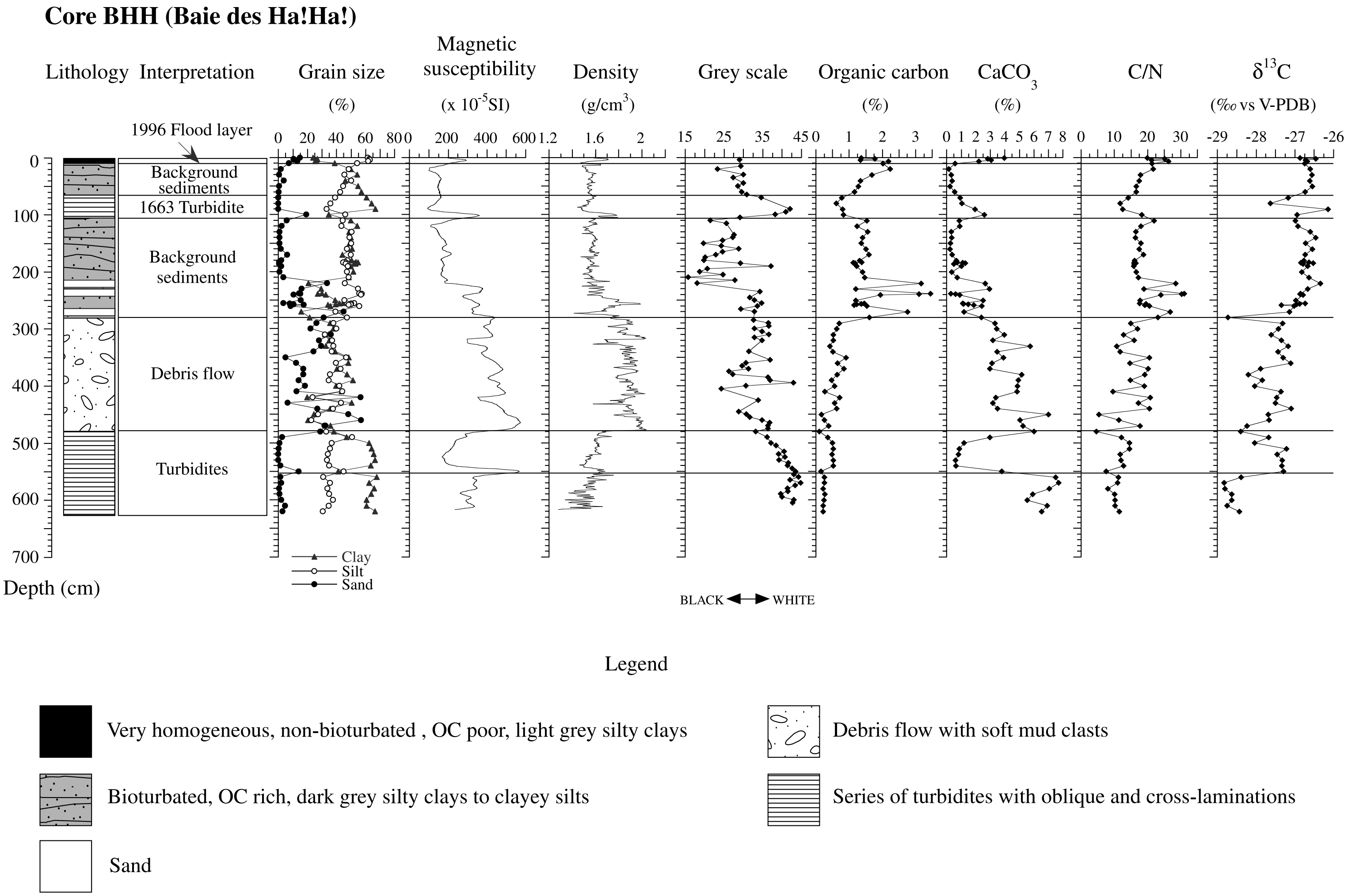

Fig. 3. Core BHH (Baie des Ha!Ha!). Lithology, core interpretation, physical, geochemical and isotopic properties. Two rapidly deposited layers are assigned to a major earthquake (dating from 1663) and to the 1996 flood. A still unidentified event triggered the turbidite–debris flow sequence found at the bottom of the core.

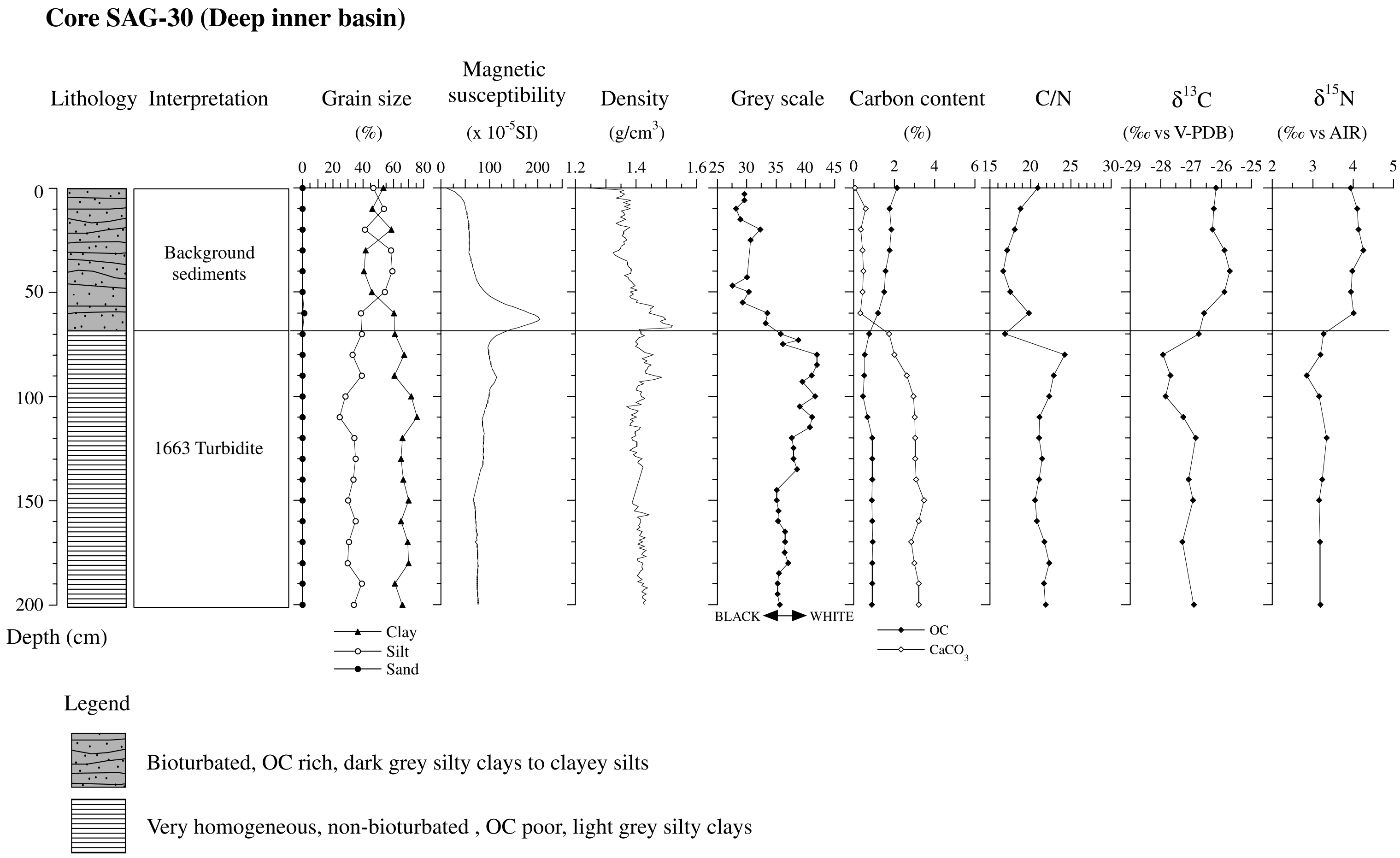

Fig. 4. Core SAG-30 (Deep inner basin). Lithology, core interpretation, physical, geochemical and isotopic properties. The rapidly deposited layer observed in this core is assigned to the 1663 earthquake.

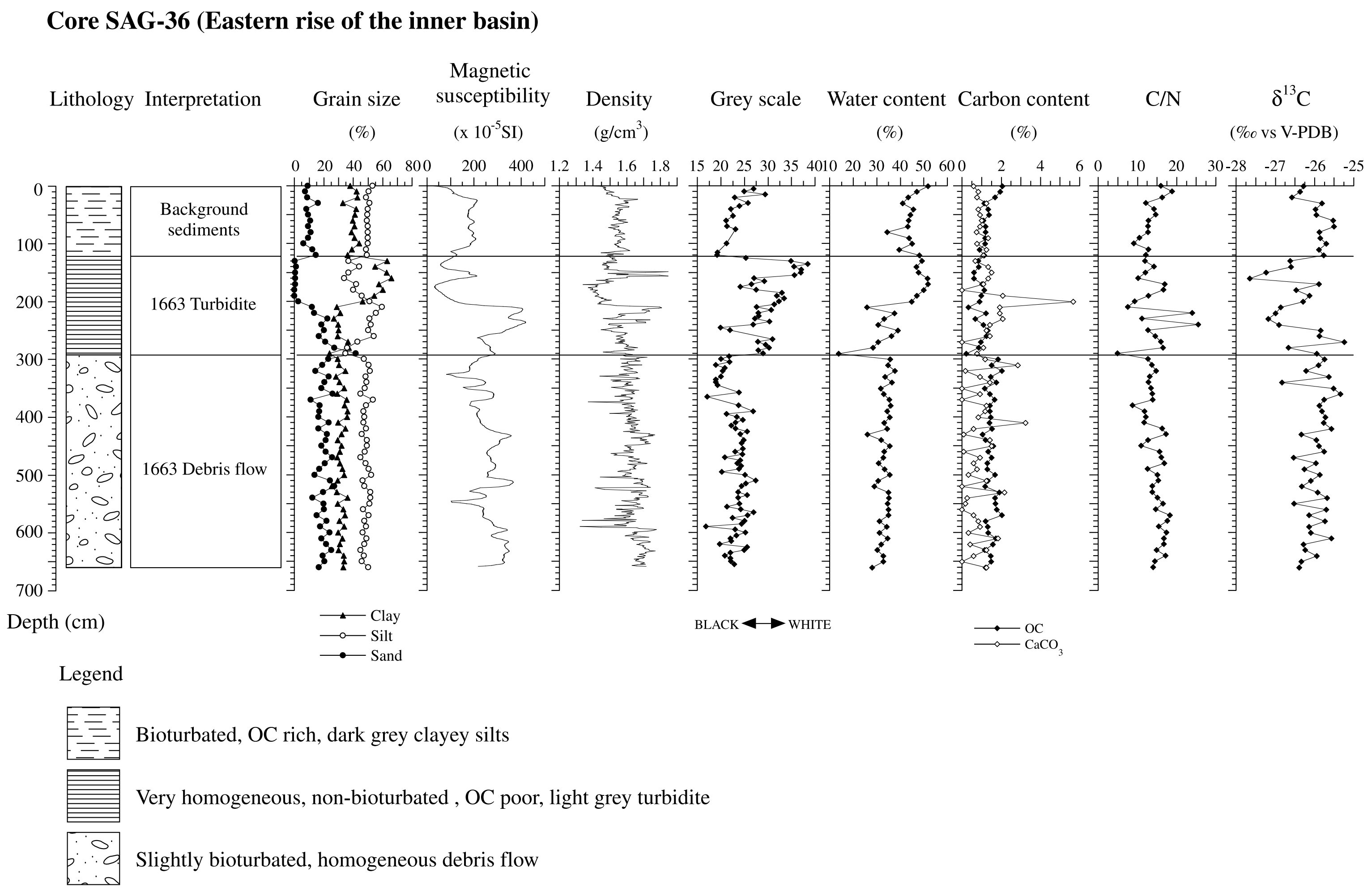

Fig. 5. Core SAG-36 (Eastern rise of the inner basin). Lithology, core interpretation, physical, geochemical and isotopic properties. The rapidly deposited layer assigned to the 1663 earthquake depicts two units: at the bottom, a debris-flow, followed by a turbidite.

homogeneous water content and relatively high and constant OC contents (~1.4%; Fig. 5). Perret et al. (1995), as well as Syvitski and Schafer (1996), observed layers with similar features in cores taken from sites in the vicinity of SAG-30. Syvitski and Schafer (1996) interpreted these layers as being debris flows triggered by the 1663 earthquake. Based on this interpretation, the bottom unit of core SAG-36 is correlated to the 1663 earthquake. The sequence comprising the interval between 122 and 296 cm downcore in core SAG-36 is a light grey, non-bioturbated, OC-poor layer with grain size becoming finer upwards, which is interpreted as a turbidite (Fig. 5). The base of this turbidite, which we correlate to the 1663 turbidite described by Perret et al. (1995) and Syvitski and Schafer (1996), is marked by a sharp colour and texture contact. The uppermost sedimentary unit of this core (122–0 cm) is composed of dark grey, bioturbated, OC-rich clayey silts. By using the depth of the 1663 turbidite, a sedimentation rate of 0.36 cm yr^{-1} is estimated for steady-state conditions at this site (RDL excluded). This is slightly greater, but compatible with the 0.24 cm yr^{-1} sedimentation rate determined using ^{210}Pb data in box core sediments from the same site (Fig. 6; Table 2). This difference is likely due to spatial variability at the site in the fjord morphology and pattern of sedimentary dispersal *and is to be expected in a high energy environment such as the Saguenay Fjord.*

4.2. Physical, geochemical and isotopic properties of rapidly deposited layers

4.2.1. The undated turbidite–debris flow bottom unit from Baie des Ha!Ha!

This composite sedimentary unit is observed only in the core recovered from Baie des Ha!Ha! and is, as a whole, characterized by a light grey colour (grey scale values ranging from 24 to 45), OC contents <1%, an average C/N ratio of 13.4 ± 4.3, relatively high $CaCO_3$ content (>6%) and minimum $\delta^{13}C$ values (as low as −28.8‰; Fig. 3).

4.2.2. The 1663 turbidite

The 1663 turbidite, observed in cores BHH, SAG-30 and SAG-36, bears almost identical features at all the three sites. This turbidite is light grey in colour, and registers grey scale values higher than background sediments (usually ranging between 30 and 40; Figs. 3–5). OC and $CaCO_3$ contents are generally lower than 1 and greater than 2%, respectively, the latter reaching values as high as 2.6% in core BHH, 3.5% in core SAG-30 and 5.7% in core SAG-36 (Figs. 3–5). The 1663 turbidite is also characterized by high C/N ratio values of 18.2, 24.2 and 25.4, in cores BHH, SAG-30 and SAG-36, respectively (Figs. 3–5). Generally low $\delta^{13}C$ values are also typical for this unit, with mean values of −26.9 ± 0.5, −27.2 ± 0.4, −26.5 ± 0.2‰ in the BHH, SAG-30 and SAG-36 cores, respectively (Figs. 3–5). It should be noted that a mean $\delta^{15}N$ value of 3.2 ± 0.1‰ measured in core SAG-30 for this turbidite is much lower than those reported by Muzuka and Hillaire-Marcel (1999) for recent sediments from the Laurentian Channel in the Estuary and Gulf of St. Lawrence (5.82–8.92‰). Finally, when present (i.e. cores BHH and SAG-36), the sandy base of the 1663 turbidite is characterized by high density and high magnetic susceptibility values (Figs. 3 and 5).

4.2.3. The Saint-Jean-Vianney landslide layer

This layer is observed only in core SAG-05 and is characterized by a mean density of 1.53 ± 0.06 g cm^{-3}, relatively low magnetic susceptibility values (mean = 24 ± 3 × 10^{-5} SI; Fig. 2), low OC contents averaging 0.93 ± 0.64%, a C/N ratio averaging 18.7 ± 6.7, minimum $\delta^{13}C$ values as low as −28.1‰ and averaging −27.4 ± 0.7‰, and elevated $CaCO_3$ values averaging 2.9 ± 2.1% (Fig. 2).

4.2.4. The 1996 flood layer

This layer is well preserved in cores SAG-05 and BHH. It has a relatively low mean magnetic susceptibility (78 ± 18 and 245 ± 36 × 10^{-5} SI, respectively; Figs. 2 and 3) and its density varies from a mean value of 1.50 ± 0.03 at SAG-05 to 1.59 ± 0.09 g cm^{-3} in the Baie des Ha!Ha! (Figs. 2 and 3). Similar to most RDL, this layer is relatively poor in OC (averaging ~1.7% at both sites) and relatively high in $CaCO_3$ content (mean values of 1.4 ± 0.6 and 2.5 ± 0.3%, in cores SAG-05 and BHH, respectively). The 1996 flood layer also has high C/N ratios (≥20) and variable, yet low $\delta^{13}C$ values. In core SAG-05, a value of −20.4‰ (checked thrice) in the uppermost subsample (0–1 cm) is responsible for the higher mean $\delta^{13}C$ value recorded in the 1996 flood layer at the site.

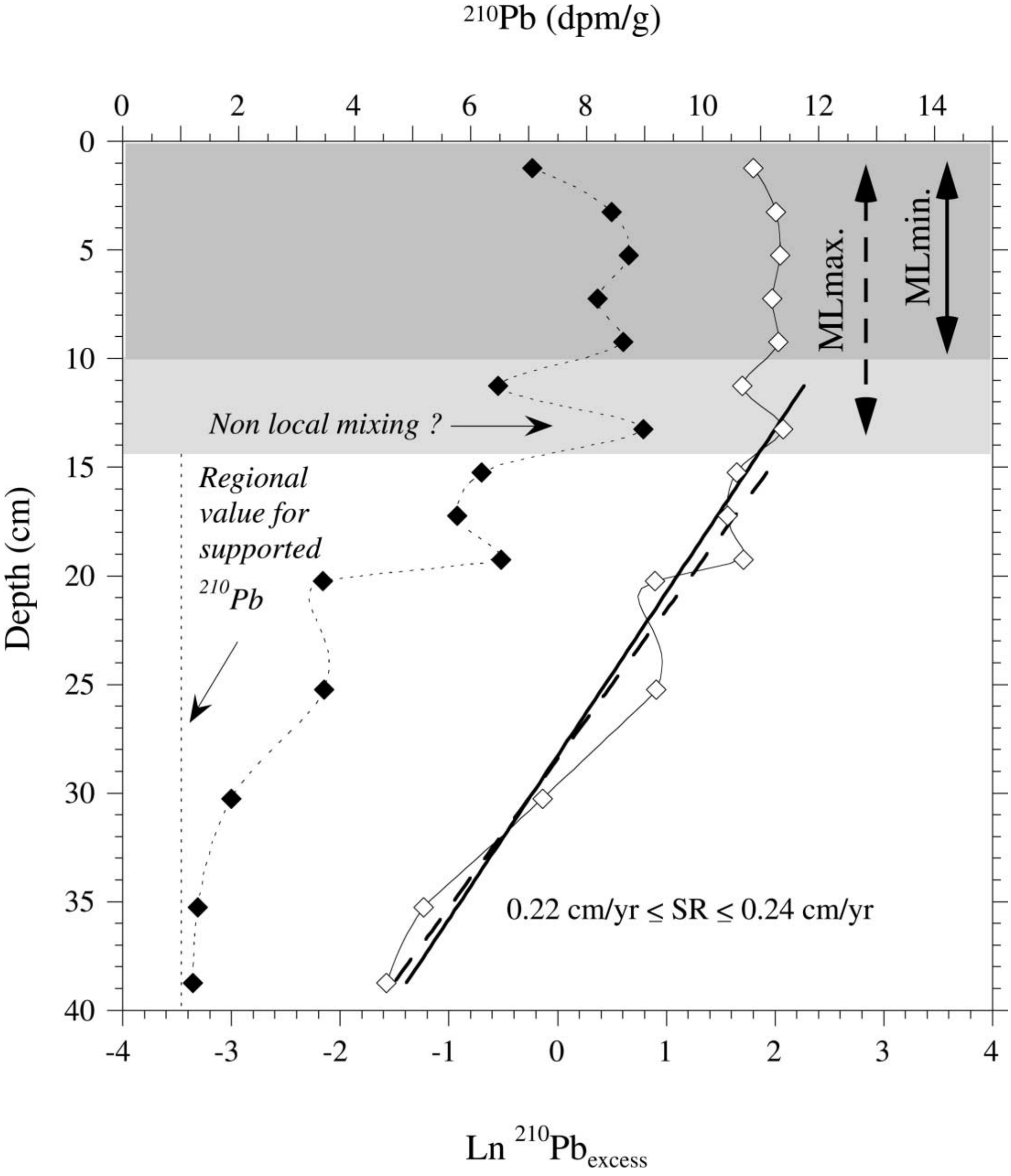

Fig. 6. Lead 210 measurements in box-core SAG-36 (Eastern rise of the inner basin). Biological mixing occurs in the upper ~10 or 15 cm (depending on the interpretation of the high value found at ~13 cm) leading to some smoothing of sedimentary records at the site. A sedimentation rate ranging between ~0.22 and 0.24 cm yr^{-1} can be estimated, depending on the depth of the mixed layer. ML = mixed layer. Regional ^{210}Pb supported value from Zhang (2000).

4.3. Geochemical properties of background sediments

Two layers representing background sediments are present in core SAG-05 from the Northern Arm (Figs. 1 and 2). The OC content of the lower unit increases almost exponentially from the base (0.7%) to the top (4.6%) of the sequence (Fig. 2). A similar pattern is observed for C/N ratios (increasing from 13 to 35; Fig.

2), while the sediment density and magnetic susceptibility show a reverse, almost exponential trend, with minimum values at the top of the layer. $\delta^{13}C$ and $CaCO_3$ values are more uniform, averaging −26.7 ± 0.1‰ and 0.4 ± 0.2%, respectively (Fig. 2). A discrete trend is detectable in $CaCO_3$ values slightly decreasing from 0.8 to 0.3%, and $\delta^{13}C$ values slightly increasing from approximately −27 to −26.6‰. The upper layer, representing background sediments (45–8 cm downcore; Fig. 2), systematically shows opposite but less pronounced trends for all the above parameters, with a slight decrease in OC contents, C/N ratios and $\delta^{13}C$ values, matching a slight increase in magnetic susceptibility, density and $CaCO_3$ values (Fig. 2).

In core BHH, two layers characterizing background sediments are observed (Fig. 3). Their physical and geochemical parameters tend to be less variable than those of the RDL of this core, with the exception of the three thin sandy layers found at the base of the lowermost of these units. Apart from these layers, the bottom sedimentary unit is characterized by relatively stable OC, C/N, $CaCO_3$ and $\delta^{13}C$ values, averaging 1.3 ± 0.1%, 17.7 ± 1.7, 1.0 ± 0.8% and −26.8 ± 0.2‰, respectively (Fig. 3). Slightly more variable geochemical properties are depicted in the upper unit consisting of background sediments. As in the Northern Arm core, discrete trends are also observed. From the base to the top, OC contents and C/N ratios increase (from 0.8 to 2.0% and from 14 to 21, respectively), whereas $CaCO_3$ contents decrease (from 0.9 to 0.6%; Fig. 3). Unlike the other parameters, $\delta^{13}C$ values in this layer do not show any clear trend and average −26.7 ± 0.2‰ (Fig. 3).

In the two cores from the inner basin (SAG-30 and SAG-36), only one sedimentary unit representing background sediments is observed. In both cores, this unit possesses relatively uniform geochemical properties, with a possible slight upwards trend for OC contents and C/N ratios. Again, no discernable trend is observed in the $\delta^{13}C$ values, which vary little and show mean values of −26.1 ± 0.3 and −25.9 ± 0.3‰, in cores SAG-30 and SAG-36 (Figs. 4 and 5), respectively. In box-core SAG-36, lead 210 measurements (Fig. 6) indicate that biological mixing occurs at least in the upper ~10 cm leading to some possible smoothing of sedimentary records at the sampling site.

5.1. Organic carbon sources in the Saguenay Fjord

The hydrological and geological setting of the Saguenay Fjord make it more complex than previously reported to characterize the sources of OM in the Fjord (e.g. Tan and Strain, 1979; Pocklington and Leonard, 1979; Louchouarn et al., 1999; St-Onge et al., 1999). Fig. 7 reveals four distinct potential sources of OM in the Saguenay Fjord sediments, some showing similar $\delta^{13}C$ values. This prevents the unequivocal identification of terrestrial and marine end-members based on this parameter only. However, as explained below, by combining C/N ratios with $\delta^{13}C$ values, these OM components can be distinguished.

5.1.1. Industrial and terrestrial OM

Analysis of recent Saguenay Fjord sediments has revealed that an important part of organic matter inputs originates from pulp and paper industry effluents (Schafer et al., 1980; Smith and Schafer, 1987; Louchouarn et al., 1997b, 1999). Schafer and Smith (1987) associated the first increase in OM concentrations in sediments to the construction of the first large paper mills in Kénogami and Jonquière, between 1910 and 1912. They also suggested that the increase in OM contents toward the surface of a gravity core from the Northern Arm was linked to the expansion of the pulp and paper industry. Furthermore, Barbeau et al. (1981) suggested that the increase in OC contents toward the surface of box cores from the Northern Arm, inner basin and Baie des Ha!Ha! was the result of increasing industrial activity, notably pulp and paper industries.

Due to contamination by paper mill discharge, the OM from recent sediments is expected to have a distinct signature. In order to constrain the geochemical properties of the pre-industrial OM, a closer look at background sediments deposited prior to the industrial period is needed. Such sediments are found in the layer underlying the 1663 RDL in core from BHH (Fig. 3). At the study site, they yielded mean $\delta^{13}C$ value and C/N ratio of, respectively, −26.8 ± 0.2‰ and 17.7 ± 1.7. These values fall into the range reported for terrestrial OM in areas where C3-plant metabolism dominates (Fig. 7; Sackett, 1964;

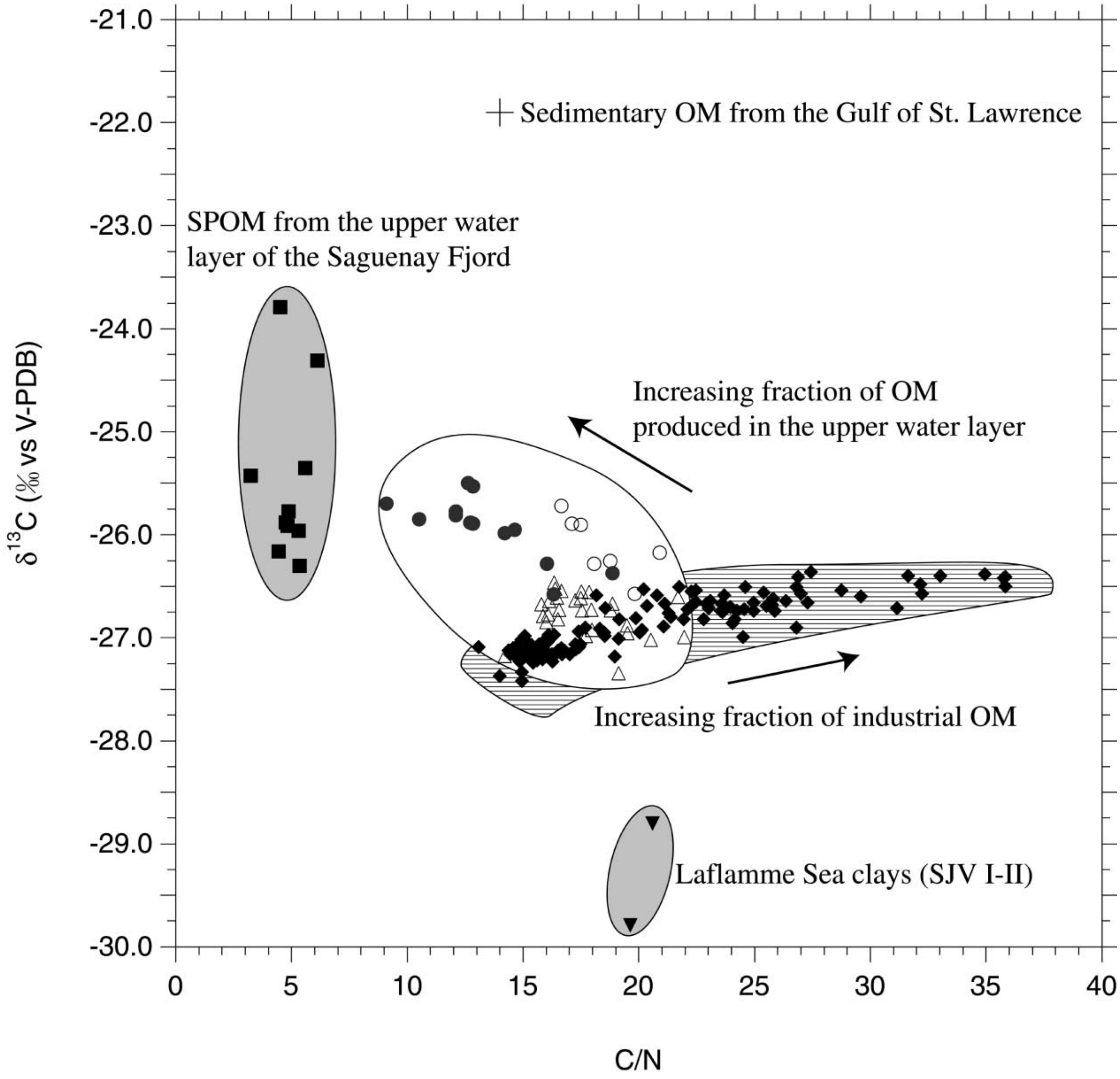

Fig. 7. Elemental and isotopic properties of sedimentary OM in Saguenay Fjord background sediments. Three distinct OM sources are identified: SPOM (data from Lamontagne, 2001) from the upper water layer, the Laflamme Sea clays and industrial OM (see also Fig. 9). Black diamonds: core SAG-05; open triangles: core BHH; open circles: core SAG-30; grey circles: core SAG-36; black triangles: Laflamme Sea clays; black squares: SPOM from St-Fulgence to SAG-42; and black cross: sedimentary OM from the Gulf of St. Lawrence (data from Muzuka and Hillaire-Marcel, 1999).

Nissembaum, 1974; Lucotte et al., 1991; Meyers, 1997). The δ^{13}C value observed here for the pre-industrial sedimentary OM (-26.8 ± 0.2‰) differs from that (-25.9 ± 0.4‰) reported by Tan and Strain (1979) for surface sediment in the inner basin of the Saguenay Fjord. The ^{13}C-enriched isotopic composition that they observed may be due to either recent contamination by OC from pulp and paper industries (see below), or to an enhanced contribution of locally produced OM (Fig. 7), or to a combination of both. In

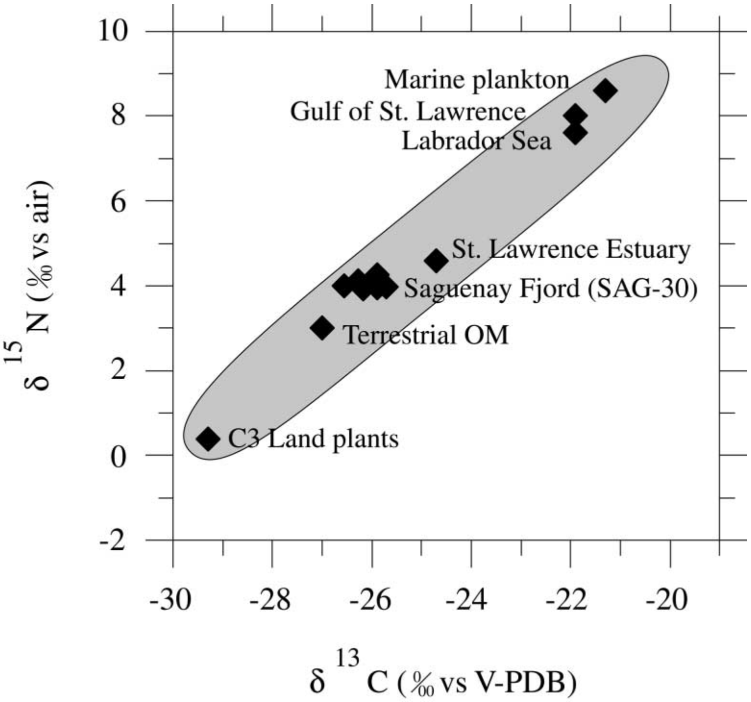

Fig. 8. δ^{13}C vs δ^{15}N of sedimentary OM. Grey area represents mixing of marine and terrestrial OM from various sites as reported by Peters et al. (1978). Additional data: C3-land plant and marine plankton end-members from Peterson and Howarth (1987); Mean terrestrial OM from Fogel and Cifuentes (1993); Labrador Sea and Gulf of St. Lawrence from Muzuka and Hillaire-Marcel (1999); Saguenay Fjord (this study); St. Lawrence Estuary (core MD99-2220, unpublished data). Modified from Meyers (1997).

a study of recent sediments from the Northern Arm and inner basin, Louchouarn et al. (1999) also concluded that most of the sedimentary OM was of terrigeneous origin, and that between 10–70% of the total lignin accumulated was anthropogenic in origin. Furthermore, the mean δ^{15}N value (4.1 ± 0.1‰) in background sediments from core SAG-30 also suggests that most of the sedimentary N is of terrestrial origin (Létolle, 1980; Gearing, 1988; Fogel and Cifuentes, 1993), as shown in Fig. 8.

Results from the present study illustrate the industrial influence on recent sediments, as shown in Figs. 7 and 9, using data from core SAG-05. An asymptotic trend for δ^{13}C values increasing with OC supplies and C/N ratios is observed (Figs. 7 and 9a). The high C/N ratios and OC content values are associated with pulp and paper discharges and represent industrial OM (Schafer and Smith, 1987; Barbeau et al., 1981; Louchouarn et al., 1999). A δ^{13}C value of −26.34 ± 0.02‰ for the contaminating OC is calculated using the *y*-intercept of the δ^{13}C vs 1/OC linear relationship (Fig. 9b).

In background sediments deposited subsequent to the 1663 earthquake in cores SAG-05 and BHH, OC contents, C/N ratios and to a lesser extent, δ^{13}C values all follow a similar evolution through time. This evolution is better seen in core SAG-05, due to its higher sedimentation rate. OC contents and C/N ratios increase almost exponentially and reach a maximum value slightly prior to the deposition of the 1971 RDL (Fig. 2). δ^{13}C values show a concordant trend towards heavier values. Above the 1971 RDL, a sharp trend towards decreasing OC contents, lower C/N ratios and lighter δ^{13}C values follows, and minimum values are reached right at the top of the unit, just below the 1996 RDL. This pattern is linked to industrial activity in the area, more specifically to the development of the paper mill and aluminium industries (Barbeau et al., 1981; Smith and Schafer, 1987; Louchouarn et al., 1997b, 1999). Increasing fluxes of ligneous debris

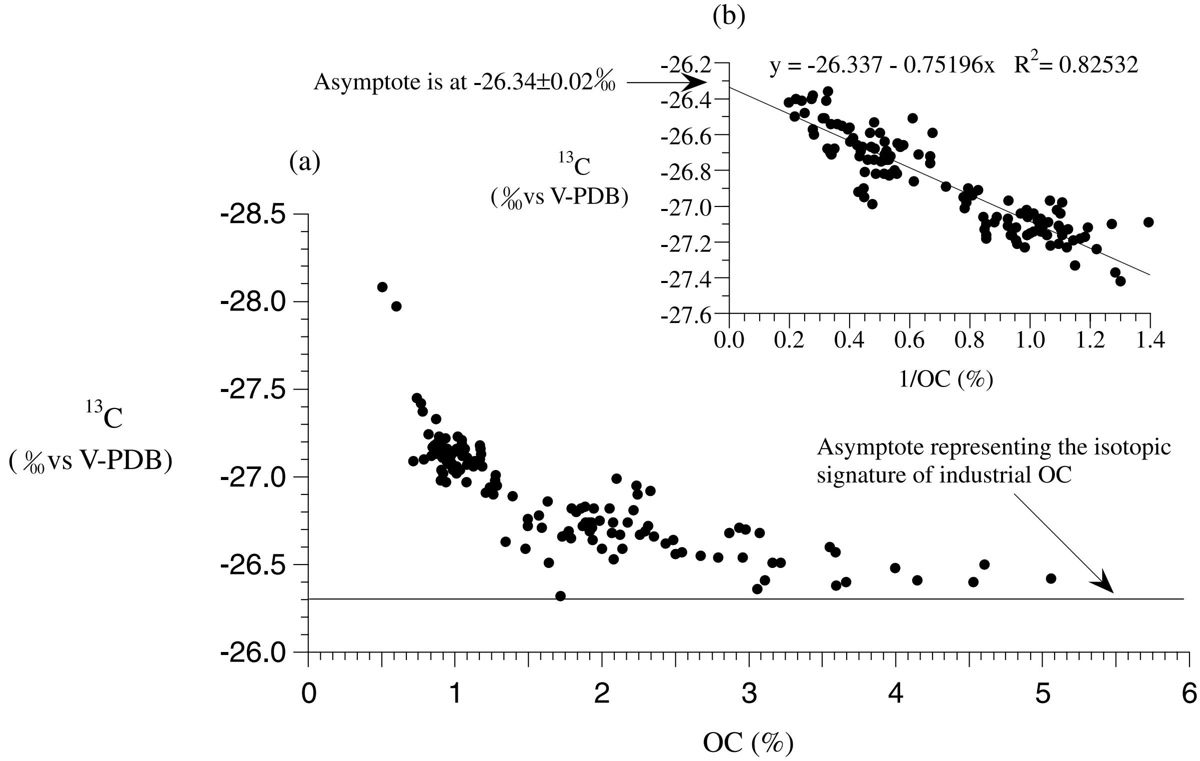

Fig. 9. Core SAG-05 (Northern Arm). δ^{13}C vs OC values in recent sediments from the Saguenay Fjord. (a) δ^{13}C vs OC showing an asymptotic trend for increasing industrial OC supplies. (b) Linear regression δ^{13}C vs 1/OC used to calculate the asymptotic value of −26.34 ± 0.02‰ for the industrial OC. A couple of data points illustrate supplies from reworked Laflamme Sea clays. They were excluded from the above calculation.

from paper mill effluents and of coal particles leached by run-off waters from coal-deposits along industrial wharfs may be held responsible for the trend observed below the 1971 RDL. The asymptotic δ^{13}C-OC value of −26.34 ± 0.02‰, calculated above for the contaminating carbon, indeed, fall in the range of values reported in literature for coals, lignites (Deines, 1980) and cellulose in pine (e.g. Bolin et al., 1979). Slightly lower values are reported for cellulose in spruce (e.g. Bolin et al., 1979). The high C/N ratios (>35) observed in sediments underlying the 1971 RDL at SAG-05 (Fig. 2) are fairly close to values reported for spruce and pine debris (Meyers, 1994) and further support the assignement of recent OM supplies to industrial activity in the Saguenay Fjord. The replacement of coal by oil since the mid-1960s (Barbeau et al., 1981), and the implementation of government environmental regulations during the 1970s and later on, resulted in drastic reductions of particulate OM discharge in the fjord (Savard, 1989; Hébert, 1995). This is illustrated here by the decreasing trends in OC contents, C/N ratios and δ^{13}C values observed above the 1971 RDL (e.g. Fig. 2).

5.1.2. Laflamme Sea clays

Another source of OM may occasionally be involved, namely the OM inherited through the reworking of sediments from the Laflamme Sea. This OM shows ^{13}C-depleted signatures, with δ^{13}C values ranging from −28.8 to −29.8‰, and a mean C/N ratio of 20.1 ± 0.7 (Table 3; Fig. 7). The influence of this source of OM will be prominent in RDL (see below), but seems of minimal importance in background sediments. The low δ^{13}C values and relatively high C/N ratios of the Laflamme Sea clays could be explained by diagenetic alteration of their original OM, rather than by a significant input of

Table 3
Mean geochemical and isotopic composition of background sediments and Laflamme Sea clays with accumulation rates of sedimentary OC

Core/sample	Interval (cm)	SR[a] (cm yr^{-1})	DBD[b] (g cm^{-3})	Total OC (%)	$CaCO_3$ (%)	C/N	$\delta^{13}C$ (‰)	TOC Ar[c] (gC m^{-2} yr^{-1})
Background sediments								
SAG-05	10–44	1.5	0.80	2.4 ± 0.5	0.4 ± 0.2	23.9 ± 3.6	−26.7 ± 0.1	291.6
BHH	20–70	0.2	0.87	1.4 ± 0.5	0.4 ± 0.3	17.4 ± 2.5	−26.7 ± 0.2	24.53
SAG-30	0–70	0.2	0.60	1.7 ± 0.3	0.4 ± 0.2	18.4 ± 1.5	−26.1 ± 0.3	18.72
SAG-36	0–120	0.3[d]	0.86	1.3 ± 0.3	0.9 ± 0.2	13.4 ± 2.6	−25.9 ± 0.3	34.57
Laflamme Sea clays								
SJV-I[e]	–	–	–	0.3	6.2	19.6	−29.8	–
SJV-II[e]	–	–	–	0.3	5.6	20.6	−28.8	–

[a] Sedimentation rate (from Table 2).

[b] Dry bulk density. Calculated with the mean wet bulk density and the mean water content in each selected interval.

[c] TOC Ar = Total OC accumulation rate. Calculated using SR, DBD and Total OC.

[d] Calculated using the two values from Table 2.

[e] Both samples were taken from the original Saint-Jean-Vianney landslide location, NW of Chicoutimi (Fig. 1).

terrigenous OM during their deposition. The Laflamme Sea clays where deposited during a period of reduced vegetation, due to the harsh conditions at the front of the retreating glacier (Richard, 1985). Several studies have documented similar decrease in $\delta^{13}C$ values in relation to preferential losses of isotopically heavy organic material compounds such as carbohydrates and proteins (e.g. Hatcher et al., 1983; Spiker and Hatcher, 1984, 1987).

The lowest $\delta^{13}C$ value (−28.8‰), matching the highest $CaCO_3$ content (7.7%), is observed in the lowermost turbidite–debris flow sequence of unknown age in core BHH. These values are not seen elsewhere in the Fjord, nor in the 1663 turbidite from the same site. This suggests a different source for the sedimentary OC in the lower turbidite–debris flow sequence.

The best candidate for this OC source material is the Laflamme Sea clays (Fig. 7). Sediment samples from the original Saint-Jean-Vianney landslide indeed yielded a mean $\delta^{13}C$ value of −29.3 ± 0.7‰ and a mean $CaCO_3$ content of 5.9 ± 0.4% (Table 3).

Most RDL contain significant amounts of reworked $CaCO_3$ and have low overall $\delta^{13}C$ values, suggesting at least partial supplies from the Laflamme Sea clays. This is illustrated in core SAG-05 where geochemical and isotopic properties of the 1971 RDL are similar to those of the Laflamme Sea clays (Table 3). Significant departure from this pattern are the RDL deposited by the 1996 flood and the uppermost turbidite from the bottom turbidite sequence of core BHH, which both show a lesser ^{13}C-depleted OC and a lower $CaCO_3$ content. An OC source slightly different from those of the other RDL seems involved here. Nevertheless, a lesser influence of reworked Laflamme Sea clays is probable in both units.

5.1.3. OM production in the upper water layer

Suspended particulate organic matter (SPOM) of the shallow upper water layer has been collected from St-Fulgence to SAG-42 in September 2000 (Lamontagne, 2001). Isotopic and elemental analysis yielded C/N ratios and $\delta^{13}C$ values falling into a range intermediate between those of lacustrine and marine algae (Fig. 7; see Meyers, 1997). In view of the salinity of the upper water layer (0–10), such values are likely due to local production of 'brackish water' OM, although transported OM from upstream lakes and rivers could also contribute to this SPOM. This locally produced OM could be responsible for the trend towards low C/N ratios and relatively high $\delta^{13}C$ values that is depicted by background sediments from cores SAG-30 and SAG-36 (Fig. 7). However, a combination with mixed supplies from upstream fresh water settings and of marine OM cannot be totally discarded. The latter could be either transported by deep currents (see below), or originates from local production in the lower, more saline (27–31) water layer. Microfossil assemblages of background sediments of core SAG-30 indicate a mixture of freshwater and marine organisms, with diatom valves and dinoflagellate cysts reaching, concentrations of, respectively, 40×10^6 valves cm^{-3} and 1600 cysts cm^{-3} (St-Onge et al., 1999). Côté and Lacroix (1979) showed that the photic zone rarely exceeds 10 m in the Saguenay Fjord. This suggests that most of the primary production occurs in the upper water layer and that micro-organisms living below the pycnocline in the underlying more saline layer are mostly heterotrophic. However, since most dinoflagellate cysts observed in the fjord sediments correspond to heterotrophic species (St-Onge et al., 1999), they could live along the pycnocline or below it, and feed on OM produced above, mainly by diatoms. Therefore, based on the δ^{13}C values and C/N ratios of the SPOM from the upper water layer (Fig. 7), one can only identify a local OM source without more precision.

5.1.4. Marine OM from the Gulf of St. Lawrence

Another source of sedimentary OM possibly involved here is the marine SPOM from the Lower Estuary and Gulf of St. Lawrence that could be transported into the bottom water mass of the Fjord by the deep saline landward flowing waters of the Lower Estuary (Drainville, 1968). Analysis of several box cores from the Gulf and the Estuary of the St. Lawrence, by Muzuka and Hillaire-Marcel (1999), yielded a C/N ratio and a δ^{13}C value in sedimentary OM, of respectively, 13.9 ± 2.5 and -21.9 ± 0.4‰. The δ^{13}C value is almost typical of marine sedimentary OM (e.g. Meyers, 1997), whereas its C/N ratio either suggest some mixing between terrestrial and marine OM, or some diagenetic effect (or both). Other studies yielded similar δ^{13}C values (-21.5 ± 0.8‰) in SPOM sampled with vertical plankton tows in the Lower Estuary (Tan and Strain, 1983), with mean C/N ratios of fine grained sediments (<0.05 mm) decreasing from 12.7 in the Lower Estuary to 8.5 in the Gulf of St. Lawrence (Pocklington and Leonard, 1979). Based on such data (Fig. 7), the contribution of long distance transported marine OM to the Saguenay Fjord background sediments seems probably negligible.

5.1.5. C4-plant inputs

Occasional inputs of OM from marsh C4-plants (δ^{13}C: -15 to -12‰, Ostrom and Fry, 1993), such as *Spartina* sp. (Rousseau, 1974; Lucotte, 1989), cannot be totally discarded either. Evidence of inputs from C4-plant may be found at the very top of core SAG-05. Here, a δ^{13}C value of -20.4‰ is significantly higher than values previously reported by Tan and Strain (1979) for the Saguenay Fjord sediments or than OM produced locally in the overlying water layer (Fig. 7). It could indeed respond to incorporation of small quantities of OM from C4-plants into the Saguenay Fjord sediments, as observed for example in sediments from the Upper Estuary of the St. Lawrence, by Lucotte (1989).

5.2. Organic carbon burial rates in the Saguenay Fjord

Based on the sedimentation rates estimated above (Table 2), burial rates for total OC (TOC) were calculated at each site, for the pre-1996, post-1663 background sediments (Table 3). Values of ~35, 20 and 25 gC m^{-2} yr^{-1} are obtained for TOC burial rates in cores SAG-36, SAG-30 and BHH, respectively, contrasting sharply with the ~290 gC m^{-2} yr^{-1} value estimated for core SAG-05. This is simply due to the one order of magnitude higher sedimentation rate at the latter location. These burial rates are one to two orders of magnitude higher than those estimated by Muzuka and Hillaire-Marcel (1999), Louchouarn et al. (1997a) and Silverberg et al. (2000) in the Gulf of St. Lawrence (Table 4). Assuming a surface area of 24 km^2 (calculated using Surfer 7™ software) and 101 km^2 (from Gobeil, 1999) for Baie des Ha!Ha! and the inner basin of the Saguenay Fjord, respectively, and using burial rates from cores BHH and SAG-30 (Table 3), approximately 0.59 and 1.89 Gg of OC are annually buried in the Baie des Ha!Ha! and the inner basin of the Saguenay Fjord, respectively. The latter value represents a minimum value since burial rates are increasing towards the head of the fjord due to higher sedimentation rates.

The high sedimentation rates of the fjord sediments, along with the refractory nature of the OM, suggested by its high C/N ratios, may account for the overall minimum diagenetic alteration, high preservation rates and high burial rates for OC. In fact, no geochemical or isotopic evidence for significant OC diagenetic alteration has been found in background sediments.

Table 4
Particulate organic carbon burial rates for various sites in the Saguenay Fjord and Gulf of St. Lawrence

Location	Reference	Burial rate ($gC\ m^{-2}\ yr^{-1}$)
Saguenay Fjord (core SAG-05)	This study	291.6
Saguenay Fjord (core BHH)	This study	24.53
Saguenay Fjord (core SAG-30)	This study	28.08
Saguenay Fjord (core SAG-36)	This study	29.96
Laurentian Channel (Sites 12–21)	Muzuka and Hillaire-Marcel, 1999	0.765–2.501 (1.469)[a]
Laurentian Channel (Station 019)	Louchouarn et al., 1997a,b	2.02–4.04[b]
Laurentian Channel (Station 001)	Louchouarn et al., 1997a,b	3.57
Anticosti Channel (Station 016)	Louchouarn et al., 1997a,b	0.67–0.84[b]
Anticosti Gyre (Station 1)	Silverberg et al., 2000	5.52
Cabot Strait (Station 3)	Silverberg et al., 2000	6.36
Emerald Basin (Station B)	Silverberg et al., 2000	5.76

[a] Minimum and maximum values, with the average in parentheses.

[b] Minimum and maximum values.

5.3. Incidence of rapidly deposited layers on organic carbon preservation

OM contents in the Saguenay Fjord background sediments, prior to 1663 (i.e. to any industrial influence; e.g. core BHH; Fig. 3) seems to have undergone negligible diagenetic evolution, as illustrated by the very flat OC contents and relatively constant C/N ratios and $\delta^{13}C$ values in core BHH, below the 1663 turbidite (excluding the three thin sandy layers; Fig. 3). High OC preservation rates can be attributed here to the fast overall sedimentation rates and the frequent occurrence of RDL. These RDL result notably in a reduction of biological mixing of the underlying sediments, thus reducing oxidation rates for the buried OC. Physical property studies and visual observation of RDL in the study cores and in box-cores from complementary studies (e.g. Savard, 2000), show evidence for minimum biological mixing of underlying sediments following the deposition of RDL as thin as 8–10 cm (e.g. 1971 or 1996 layers in core SAG-05), a feature also noted by Mucci and Edenborn (1992) in a core sampled at site SAG-05.

Some of the RDL can be very thick. For example, the 1663 turbidite in core MD99-2222, sampled on board the Marion Dufresne II, and raised near core SAG-30, is almost 16 m (Hillaire-Marcel and Turon, 1999). These layers usually show uniform OC ($\sim 1\%$) and $CaCO_3$ ($>2\%$) contents. Thus, due to both their frequent occurrence and thickness, these layers may represent a significant component for the burial of both forms of carbon (OC and $CaCO_3$) in such a transitional environment.

From a methodological view point, our study allowed the determination of precised sedimentological and geochemical signatures for the rapidly deposited layers (RDL) linked to earthquakes, floods and landslides. The physical properties of the sediment already permit the fast identification of such layers. Here, the reflectance is a good indicator, this because RDL incorporate significant proportions of reworked material from the postglacial Laflamme Sea clays. These clays yield a light colour drastically differing from the background fjord sediments. Among other physical parameters, magnetic susceptibility and density also allow a quick identification of RDL containing turbidites, as they are highly sensitive to density gradients and grain size variations. Moreover, the geochemical parameters used in this study also responded sensitively to the deposition of RDL. These layers all show relatively low OC, high $CaCO_3$ contents, high C/N ratios and low $\delta^{13}C$-OC values, which provide additional information on the source material. Concerning the major issue of the present study, the OC sources and burial rates, it seems that the industrial activity of the last century, notably the paper mill industry, has been responsible for drastic changes in the sedimentary dynamics of OC. This is depicted, for example, by the asymptotic δ^{13}C-OC relationship in cores near major industrial areas (core SAG-05). From this view point, all geochemical indicators point to the conclusion that the implementation of environmental regulations and the improvement of industrial practices, during the mid-1960s and later on, resulted in OC fluxes decreasing to values near pre-industrial level within a few decades. Indeed, following the almost exponential increase in OC contents, C/N ratios and δ^{13}C-OC values observed during the industrial period, a fast drop in these parameters is observed since the deposition of the RDL assigned to the Saint-Jean-Vianney landslide, i.e. since the beginning of the 1970s.

In terms of the role of fjords such as the Saguenay Fjord with respect to OC burial, all are likely to represent an important carbon sink due their overall high sedimentation rates. However, in the Saguenay Fjord, another sedimentological property seems to enhance OC preservation and burial: the frequent occurrence of fast sedimentological events leading to the deposition of relatively thick units sealing the underlying OC-rich sediments. Here, the geological setting of the Saguenay Fjord is the key element. The fjord lies in a major structural depression and has experienced several strong magnitude earthquakes. They resulted in the frequent deposition of thick turbidites and debris flows. In addition, the presence, around the head of the fjord, of marine terraces composed of 'quick' clays, led to major landslides spreading large amounts of reworked material into the fjord. Finally, the relatively large watershed of the Saguenay river has also induced floodings, as in 1996, with focussing of large amounts of terrigeneous material into the relatively short and narrow fjord basins. Both the high sedimentation rates and frequent fast sedimentological events result in exceptionally high OC burial rates in the Saguenay Fjord, ranging from one to two orders of magnitude above those reported elsewhere for the Estuary and Gulf of St. Lawrence. Continental margins, and particularly shelves, are often evoked as major OC burial sites. The present example suggests that they are likely to be characterized by highly variable burial rates, and that a few OC focussing spots may play most of this role.

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