Oceanography and Quaternary geology of the St. Lawrence Estuary and the Saguenay Fjord

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Oceanography and Quaternary geology of the St. Lawrence Estuary and the Saguenay Fjord

Anne de Vernal[1], **Guillaume St-Onge**[2] **and Denis Gilbert**[3]

[1] GEOTOP, Université du Québec à Montréal, P.O. Box 8888, succursale "centre ville" Montréal, QC, H3C 3P8 Canada

[2] GEOTOP and Institut des Sciences de la Mer (ISMER), Université du Québec à Rimouski, 310, Allée des Ursulines, Rimouski, QC, G5L 3A1 Canada

[3] Institut Maurice-Lamontagne, Pêches et Océans Canada, 850 route de la Mer, CP 1000 Mont-Joli, QC, G5H 3Z4 Canada

E-mail: devernal.anne@uqam.ca

Abstract. The St. Lawrence Estuary is an environment marked by important freshwater discharge and well stratified water masses, recording large seasonal contrast in surface waters from freezing conditions in winter to temperate conditions in summer due to a very strong seasonal cycle in overlying air temperature. High productivity takes place in the pelagic and benthic environments, where a recent trend toward bottom water hypoxia is observed. The area was profoundly marked by the Quaternary glaciations. Thick glaciomarine sequences dating from the last deglaciation are observed in the Estuary and along the shores, whereas a relatively thin layer (a few meters at most) of hemipelagic mud was deposited during the Holocene.

1. Introduction

The St. Lawrence Estuary is a transitional environment between the St. Lawrence River and the northwest North Atlantic Ocean [1, 2]. It is characterized by strong stratification of water masses. The low salinity surface layer is marked by a large amplitude gradient of temperatures, freezing in winter and reaching up to 18°C in summer. The St. Lawrence Estuary is unique from several points of view. It shows features typical of polar environments despite its geographical location between 47 and 50°N. Seasonal sea-ice cover develops for several months each year and the fauna includes cold water species such as harp seals and beluga whales [3, 4]. Alpine tundra vegetation occurs at moderately low altitudes on the north and south shores [5]. Moreover, the landscape is profoundly marked by past glacial activity. For example, the Laurentian Channel (Figure 1) and the Saguenay Fjord are valleys resulting from glacial erosion [6].

In the present paper, we describe the main oceanographic features of the Estuary and Gulf of St. Lawrence. We briefly discuss the methodological difficulty of conducting paleoceanographic investigations in such an estuarine environment and provide a few references to regional studies. Finally, we present the issue of bottom water hypoxia.

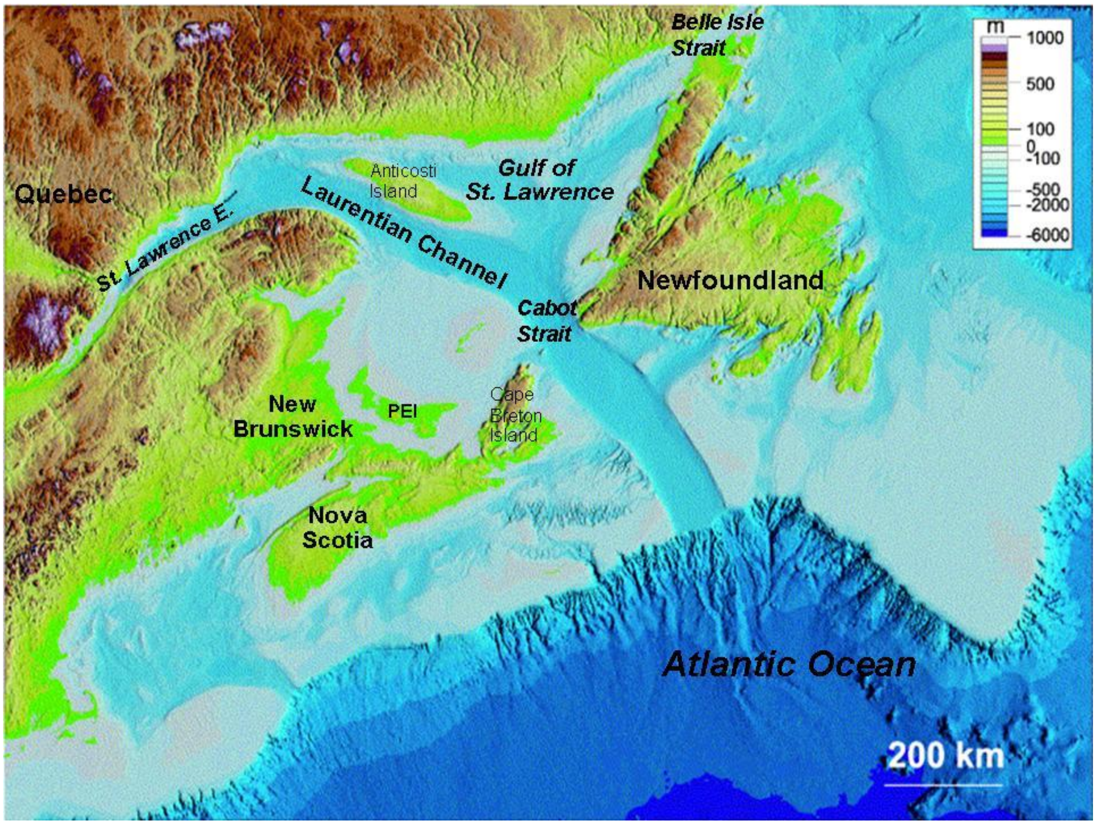

Figure 1. Map of eastern Canada showing the Estuary and the Gulf of St. Lawrence adapted from Shaw et al. [7].

2. Oceanographic context of the Estuary and Gulf of St. Lawrence

The St. Lawrence Estuary and Gulf form together an epicontinental sea making the transition from land to the northwest North Atlantic Ocean. It is characterized by a very large watershed (Figure 2) and a mean freshwater discharge of 10 900 $m^3 s^{-1}$ [8].

The circulation in the Estuary and Gulf of St. Lawrence is typical of estuarine systems and results in strong water masses stratification. The water column extends down to 500 m in the Laurentian Channel. It is characterized by three water layers (Figure 3). The upper one forms a thin surface layer (< 50 m) and flows seaward. It is marked by low salinity (27-31.5) due to the mixing of seawater with the freshwater runoff. As a consequence of stratification, the surface layer is relatively thin [9] and thus characterized by a low thermal inertia: it freezes in winter for up to 3 or 4 months per year and warms up to 18°C in summer. Seasonal gradients of temperature and productivity are thus extremely high [10]. Below the surface water, a cold intermediate layer extends down to about 150 m (Figure 4). This cold intermediate layer is closely related to climate conditions since it originates from winter cooling and water density increase in addition to brine release during sea-ice formation [9, 11]. Below the intermediate layer, warmer (4-6°C) and saltier (~ 34.5) waters occupy the Laurentian Channel. These waters originate from the mixing of the Labrador Current Water (LCW) and the North Atlantic Central Water (NACW) along the continental margin and form the St. Lawrence bottom waters [2]. The bottom waters flow landward, towards the head of the Laurentian Channel in the lower St. Lawrence Estuary near Tadoussac at the mouth of the Saguenay Fjord. The head of the Laurentian Channel is thus characterized by upwelling, which results in extremely high productivity suitable for the development of large whale populations.

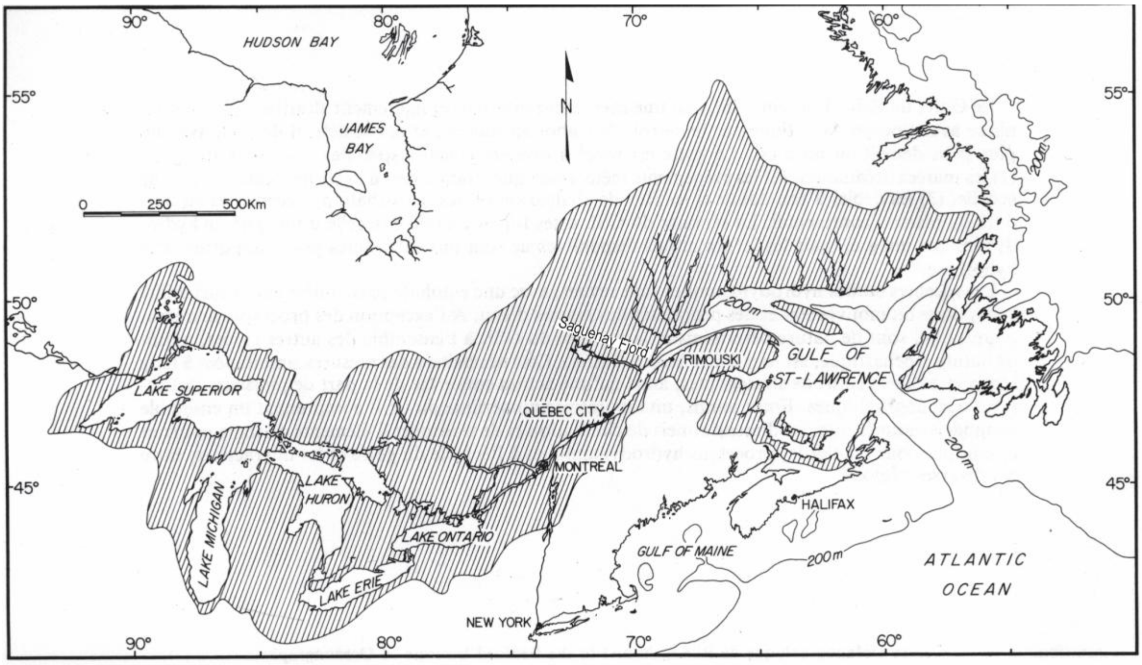

Figure 2. Map of eastern Canada showing the extent of the Gulf of St. Lawrence watershed adapted from Koutikonsky and Bugden [1].

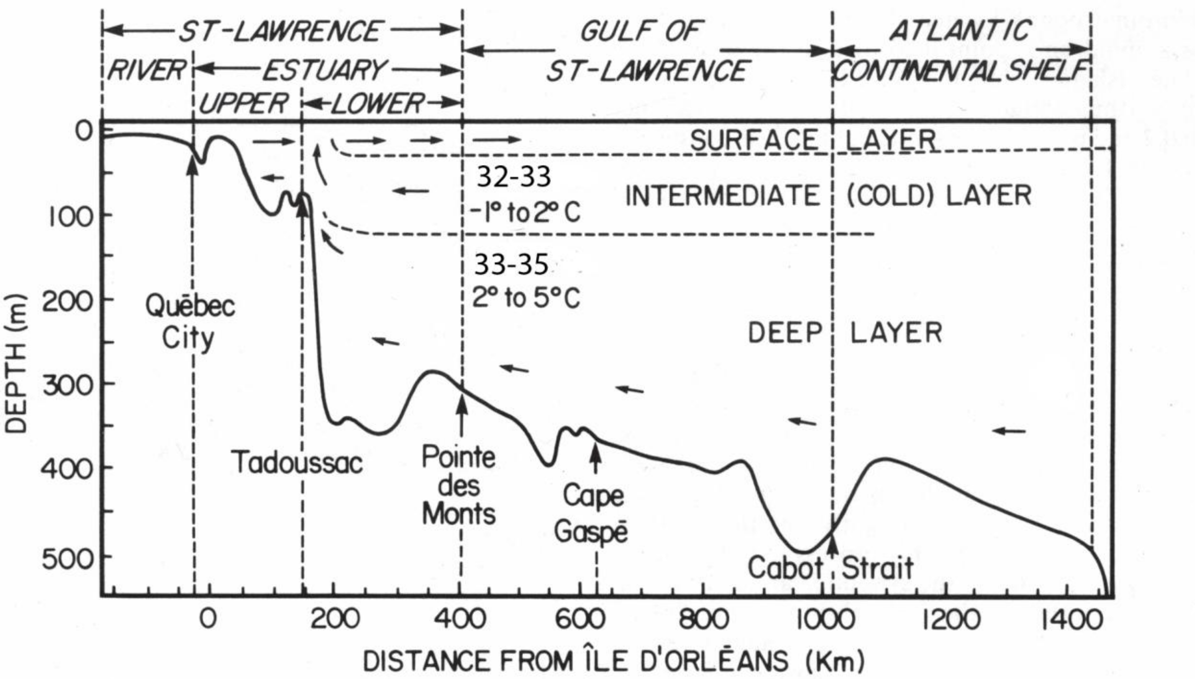

Figure 3. Schematic illustration of water masses in the St. Lawrence system (from the River to the Ocean) adapted from Koutikonsky and Bugden [1].

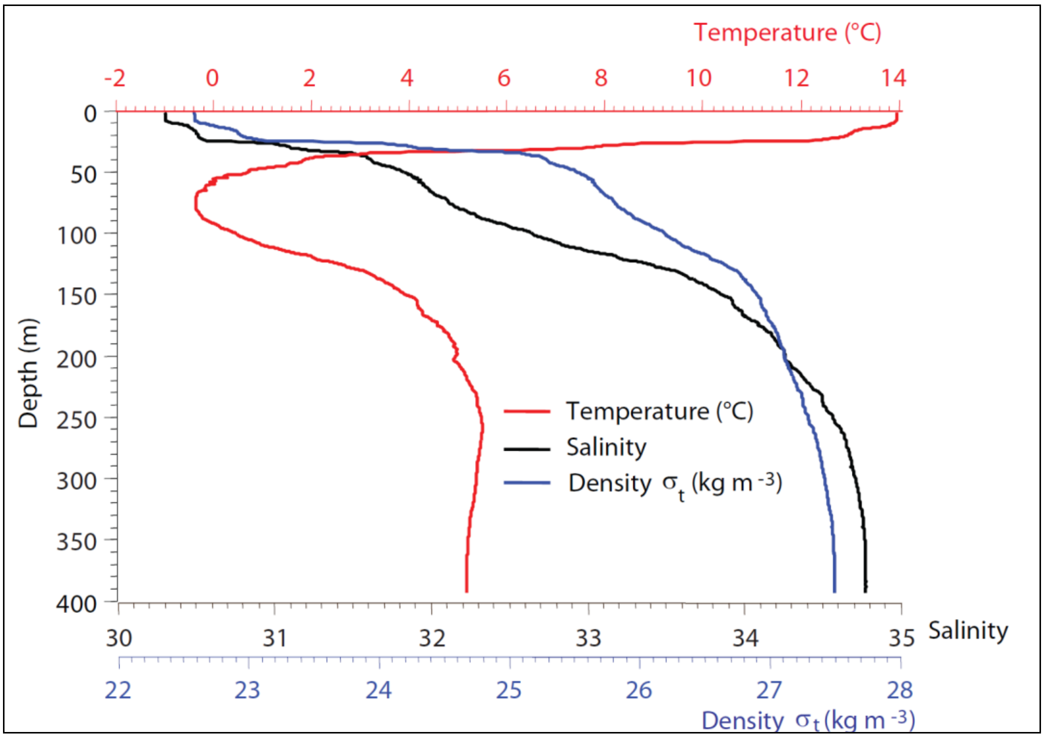

Figure 4. Summer salinity, temperature, and density profile in the Lower St. Lawrence Estuary.

In the St. Lawrence Estuary, the primary productivity is largely dominated by diatoms accompanied by dinoflagellates [12]. Protists forming calcareous shells such as coccolithophorids and planktic foraminifers, which are usually common in surface waters of mid latitude oceans, are rare in the upper water column, probably because of the low surface salinity. Among planktonic foraminifers, *Neogloboquadrina pachyderma* left-coiled is the most common species. The occurrence of this polar species, which is adapted to develop in the mesopelagic layer, appears compatible with the cold conditions of the intermediate and bottom water layers where the salinity range is also suitable. Benthic foraminifers are usually recovered in relatively high numbers in sediments [13]. However, the preservation of calcium carbonate is often an issue because of large organic carbon fluxes [14, 15]. The degradation of organic matter by oxidation results in CO_2 production, thus lowering the pH in the sediment and contributing to calcium carbonate dissolution.

3. Hydrography of the Saguenay Fjord

The Saguenay Fjord joins the Lower St. Lawrence Estuary near Tadoussac. The fjord is almost 80 km long and forms deep basins reaching 275 m of depth. It is separated from the Estuary by a sill about 25 m deep. Because of the large drainage basin with mean annual discharge of about 1500 m^3/s [16], the salinity gradient is particularly sharp. The shallow surface layer (~10 m) is characterized by a salinity of about 0 near the head to 29 at the mouth of the fjord (Figure 5). The surface water freezes in winter and reaches up to 16°C in summer.

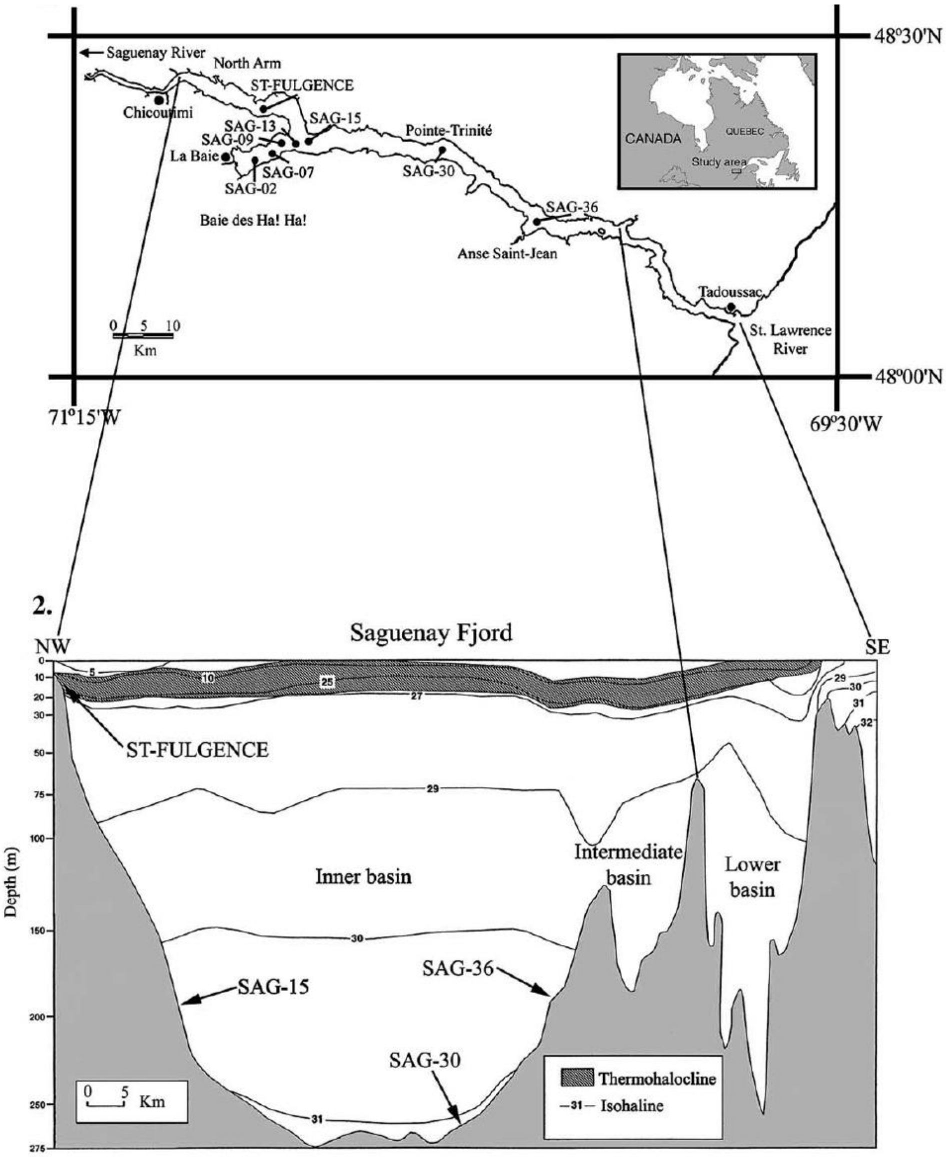

Figure 5. Map of the Saguenay Fjord and profile of salinity in the water column. Reprinted from [14], with permission from Elsevier.

The carbon fluxes in the fjord are high and largely dominated by terrestrial organic matter as shown from isotopic data and micropaleontological assemblages [17, 18]. As in the Estuary, the protist assemblages are dominated by diatoms. The diversity of dinoflagellates is low and cysts of heterotrophic taxa are common in the sediments. Benthic foraminifer shells are rare and there is evidence for dissolution of calcium carbonate. The importance of $CaCO_3$ dissolution is shown by the abundance of organic linings of benthic foraminifers relative to calcareous shells [14].

4. Regional paleoceanography

The paleoceanography of the St. Lawrence Estuary or Saguenay Fjord is difficult to explore for several reasons. First, the glacial activity eroded most sediment that accumulated prior to the last deglaciation. Second, the rarity of biogenic carbonate makes it difficult to develop ^{14}C chronology and the use of $\delta^{18}O$ and $\delta^{13}C$ in foraminifers. Third, the oceanographic conditions are complex due to the estuarine character of the environment, which is marked by large amplitude gradients of temperature and salinity in time and space, both horizontally and vertically. Thus, methodological approaches should be adapted to establish a chronological framework and to make sensible paleoceanographic reconstructions.

For the establishment of chronological schemes, several approaches can be used. At the scale of the last two centuries, ^{210}Pb and ^{137}Cs measurements from core sediments collected in the Laurentian Channel from the Lower St. Lawrence Estuary permit to evaluate sedimentation rates of the order of 0.4-0.5 cm/year and a mixing depth of bioturbation of about 3-4 cm [15, 19]. On longer time scale, high-resolution paleomagnetic data using paleomagnetic secular variations (inclination and declination) and relative paleointensity calibrated against a ^{14}C time scale may be very useful [20]. Moreover, using several radiocarbon-dated cores from the head to the mouth of Laurentian Channel, Barletta et al. [21] constructed a regional paleomagnetic master curve that has the potential to be used for dating purposes. Available data from the Lower St. Lawrence Estuary show sedimentation rates of the order of 0.15 cm/year at the scale of the last 8500 years and much higher sediment accumulation rates (>3 cm/year) before, likely in relation with outwash deposition of glacio-marine and fluvio-glacial material [20]. These high sedimentation rates allowed the deposition of >450 m of sediments in the Laurentian Channel [22], where at least half the sequence was deposited after the Younger Dryas cold episode [23].

For the reconstruction of past sea-surface conditions, diatoms that are abundant in sediment can provide very useful information in the Estuary and Gulf of St. Lawrence [24]. Organic-walled dinoflagellate cysts also are useful tracers [25], whereas benthic foraminifers may help to reconstruct benthic conditions [13-15].

Most published studies on the paleoceanography of the St. Lawrence system are based on cores collected seaward in the Laurentian Channel of the Gulf of St. Lawrence and on the Laurentian Fan. At these locations, sedimentation rates are lower and the cored sediment may span longer than the Holocene. Moreover, because sea-surface salinity is higher, the use of conventional paleoceanographic tools such as the isotopic composition of foraminifers is possible. The published data from the most oceanic parts of the Gulf of St. Lawrence illustrate large amplitude changes from the last ice age to modern. They evidence extremely cold conditions, with more than 6 months/year of sea-ice cover during an interval corresponding to the Younger Dryas episode [26, 27]. They also show that the cold event corresponds to reduced meltwater outflow from the southern Laurentide Ice Sheet through the St. Lawrence Estuary axis [27].

Other studies dealing with the paleoceanography of the St. Lawrence system are based on exposure of postglacial sediments above sea-level dated of about 12 000 to 8500 years BP. During the last deglaciation, the northward retreat of the Laurentide Ice Sheet led to marine transgression in the St. Lawrence Lowlands. The Champlain and the Goldthwait seas then developed West and East of Quebec City respectively. The marine limits of the Champlain Sea reached up to 170 m in the South and 250 m in the North of its extent. Postglacial marine deposits are thus exposed to air at many locations and form terraces along the North and South shores of the St. Lawrence Estuary and throughout the St. Lawrence Lowlands. Micropaleontological and geochemical analyses of sediments from the Champlain Sea suggest environmental conditions and fauna resembling those of the modern Arctic seas during the deglaciation [28, 29, 30].

5. Hypoxia

The St. Lawrence Estuary is characterized by a strong stratification of water masses which prevents oxygen replenishment through mixing and diffusion [31]. In the Laurentian Channel, the bottom waters are isolated from the atmosphere by a permanent pycnocline situated between 100 and 150 m water depth. Under such conditions, the water gradually loses oxygen landward from Cabot Strait to Rimouski (Figure 6) through respiration and remineralization of organic matter that settles through the water column. Measurements of dissolved oxygen in the near bottom waters have shown a significant decrease from ~125 to <65 µmol L^{-1} over the past 75 years, leading to severe and persistent hypoxia [31].

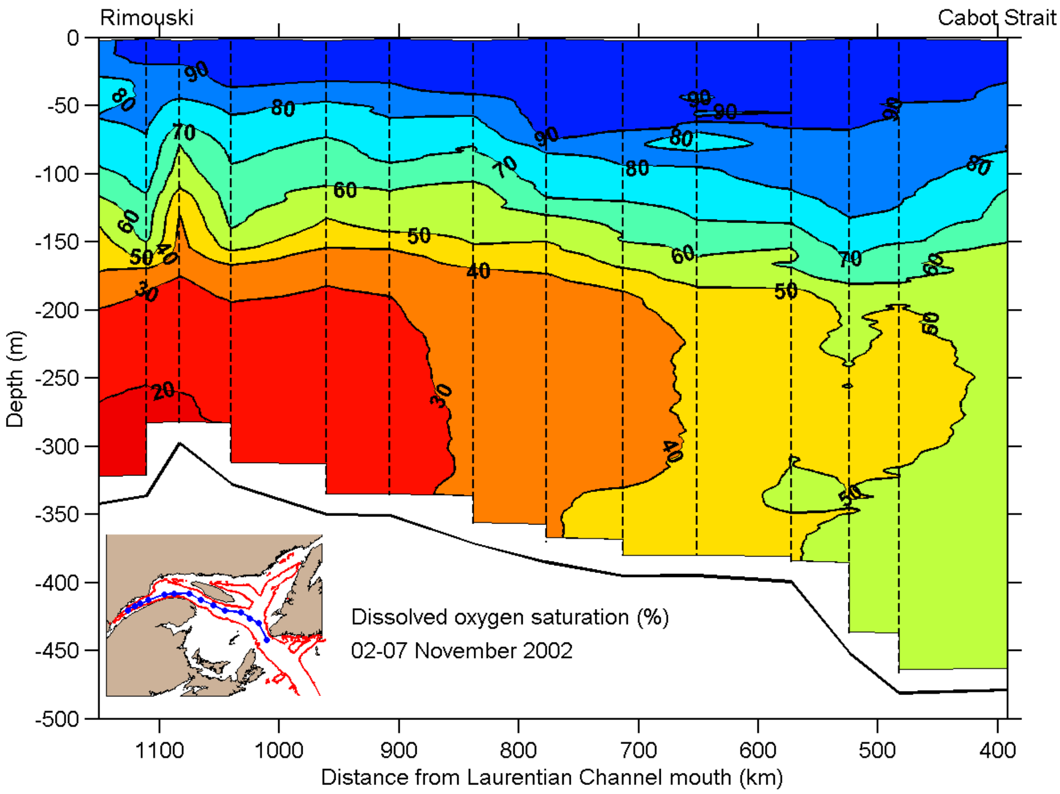

Figure 6. Contours of dissolved oxygen content in the water column of the Estuary and Gulf of St. Lawrence (adapted from [31]).

Two causes are invoked to explain the recent hypoxia. One is related to primary productivity and carbon fluxes leading to oxygen consumption during degradation of the organic matter. Eutrophication linked to enhanced nutrient input since the beginning of the industrial period has been suggested [15]. The other cause invoked is an increase in bottom water temperatures [31]. The authors attributed the bottom water warming to a decrease in the proportion of oxygen rich water from the Labrador Current and an increase in the proportion of oxygen poor water from the North Atlantic subtropical gyre thus explaining between half and two thirds of the oxygen decline in the bottom waters of the Lower St. Lawrence Estuary. In addition, this warming may have accelerated the remineralisation rate of organic matter and oxygen consumption in the water column and sediment [32, 33]. Both factors probably played a determinant role. The remaining questions are the actual part of anthropogenic forcing on eutrophication and bottom water warming and the resilience time of the system. In order to answer such questions, sedimentary cores are currently being analysed with the aim to establish centennial to millennial time series of bottom water conditions and pelagic productivity. Nonetheless, the recent work of Thibodeau et al. [34] using the isotopic composition of benthic foraminifera indicates that the recent trend observed in the bottom temperatures of the Lower St. Lawrence Estuary has no equivalent over the last millennium. Moreover, compound-specific $\delta^{15}N$ of deep-sea gorgonian corals indicates these warm temperatures may be unprecedented in the last 1800 years [35].

6. Conclusion

The St. Lawrence Estuary is a large transitional environment characterized by stratified water masses. Being under the influence of a cold temperate climate, it is marked by sea-ice formation in winter, but warm sea-surface conditions in summer. From this point of view, it is a unique environment, which has been suggested as an analogue for the northern North Atlantic during the last glacial maximum [36]. The St. Lawrence Estuary was marked by glacial erosion during the last ice age. The sedimentary sequences cored in the St. Lawrence Estuary mostly cover the last deglaciation and the Holocene. Above thick late glacial sequences, the postglacial deposits consist in a mixture of terrigenous inputs from the watershed and pelagic fluxes. The St. Lawrence Estuary is thus a particularly complex environment in which the sedimentary sequences are related to the hydrological budgets of a large watershed in addition to inflow from the northwest North Atlantic. Documenting paleoceanographic conditions in this context is a challenge. .

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