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Source: *Journal of Coastal Research*, Vol. 11, No. 4 (Autumn, 1995), pp. 1167-1179

Published by: Coastal Education & Research Foundation, Inc.

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Mineralogy, Chemistry and Particle Size Interrelationships in some Post-Glacial Marine Deposits of the St. Lawrence Lowlands

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ABSTRACT

RAMESH, R. and d'ANGLEJAN, B., 1995. Mineralogy, chemistry and particle size interrelationships in some post-glacial marine deposits of the St. Lawrence Lowlands. *Journal of Coastal Research*, 11(4), 1167-1179. Fort Lauderdale (Florida), ISSN 0749-0208.

To better characterize the nature of the source material of the present-day suspended load of the St. Lawrence River, we have examined the mineralogy and chemistry of the clay and colloid-size fractions of subaerially exposed Champlain Sea deposits and of submerged Goldthwait Sea deposits under the Upper St. Lawrence Estuary. Similar analyses were obtained on the lower St. Lawrence River and estuarine suspended sediments. The mineralogical composition, obtained from semi-quantitative X-ray diffraction studies, changes with particle size. Feldspar and quartz are predominant in the clay-size fraction, while illite and Fe-rich chlorite are abundant in the colloid-size fraction. The mineralogical composition of the clay-size material in the Champlain and Goldthwait Sea deposits is similar to that found in suspension. The marine deposits of the St. Lawrence Lowlands (Champlain and Goldthwait Sea deposits) contain the lowest mineral maturity (M_m) and chemical maturity (Ch_m) values. When compared to some of the major world rivers, it appears that mineralogically and chemically immature material is still being supplied by the St. Lawrence River under present climatic conditions. An increase in illite content, M_m , Ch_m , and a decrease in feldspar in the colloid-size fraction with increasing depth in some of the profiles investigated suggests the possibility of post-glacial diagenetic alteration. Higher chemical index of alteration (CIA) values in sediments which have been subaerially exposed as compared to those which have remained submerged may be due to ground water removal of alkalis.

ADDITIONAL INDEX WORDS: Mineral maturity, chemical maturity, St. Lawrence River, St. Lawrence Lowlands.

INTRODUCTION

Post-glacial marine transgressive deposits of the Goldthwait and Champlain Seas (13,000 to 9,000 yr BP) constitute the main surficial material of the St. Lawrence Lowlands. These deposits consist of a marginal facies made up of interlayered coarse sands and silty clays and a deep-water facies represented by massive light grey, frequently sensitive fine clays. As a result of post-glacial isostatic uplift, these relict post-glacial marine clays have provided a major source of suspended inorganic sediment to the St. Lawrence River in Holocene time. At present, the major input of solids to the St. Lawrence Estuary is the discharge of suspended particulate matter (SPM) by the St.

Lawrence River at Quebec City. The yearly input is estimated to be about 4×10^6 metric tons (MIL-LIMAN and MEADE, 1983).

The mineralogy of the Champlain Sea clays (now mostly subaerially exposed) has been investigated by various researchers (BRYDON and PATRY, 1961; GILLOT, 1971; BENTLEY and SMALLEY, 1978; LEBUIS and RISSMANN, 1979; YONG *et al.*, 1979; LOCAT *et al.*, 1984; TORRANCE, 1988) because of its influence on their geotechnical properties such as sensitivity, liquidity index, etc. General agreement now exists that the main constituents of the sediments are feldspars, quartz, and amphiboles. Illite, chlorite, amorphous oxides and carbonates are present as accessory components.

Less attention has been directed toward the mineralogy of the Goldthwait Sea clays (now in part submerged under the St. Lawrence Estuary) and the St. Lawrence River and its estuarine suspended sediments (D'ANGLEJAN and SMITH, 1973;

94061 received 5 April 1994; accepted in revision 28 August 1994.

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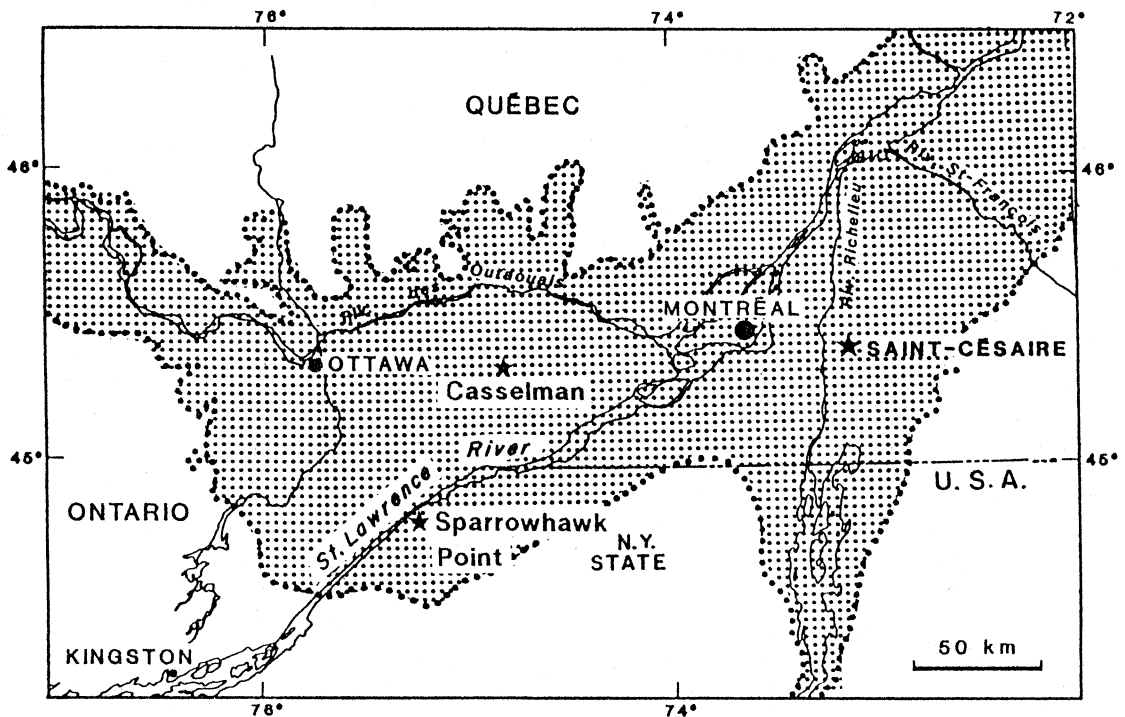


Figure 1. Map showing maximum extent of the Champlain Sea and sampling location (*) of the exposed deposits.

KONTA, 1985). D'ANGLEJAN and SMITH (1973) found temporal and spatial variations in the mineralogy and chemistry of the St. Lawrence estuarine SPM. The average clay mineral composition of the $<2 \mu\text{m}$ fraction was reported as 60% illite; 31% chlorite; 8% kaolinite and 1.5% montmorillonite. On a total-sediment basis, KONTA (1985) reported about 47% illite; 11% chlorite; 15% quartz; 4% K-feldspar; 17% plagioclase and 6% amphibole for the St. Lawrence River SPM.

Apart from these results, relatively few quantitative estimates of the mineralogy have been attempted. In particular, these studies did not provide a detailed mineralogy of the Champlain and Goldthwait Sea sediments and of its variations with depth, size and location.

Because both mineralogy and particle size control the elemental composition of riverborne sediments, the fine fractions of the source sediments and the SPM need to be compared as to their mineralogical and chemical compositions. This paper examines mineralogical and chemical vari-

ations with depth and size (clay and colloidal fractions) along six profiles in Goldthwait and Champlain Sea deposits. Similar work was carried out on samples of the SPM from the lower river and from the estuary. It is hoped that these analyses will help to better characterize the nature of the source material of the present-day suspended load of the St. Lawrence.

GEOLOGICAL ENVIRONMENT

The Goldthwait Sea occupied the St. Lawrence Estuary and Gulf from approximately 13,500 yr BP on (DIONNE, 1988). The Champlain Sea (Figure 1) flooded a basin of about 53,500 km² that occupied the isostatically depressed St. Lawrence Lowlands of Ontario, Quebec, New York, and Vermont during the final retreat of the Laurentide Ice sheet (between 12,000 to 10,000 yr BP) from eastern North America (ELSON, 1969; GADD, 1975; CRONIN, 1977; HILLAIRE-MARCEL, 1979). The areal extent of these marine basins has been controlled by three factors: (1) retreat of the ice sheet; (2)

glacial isostatic recovery and (3) globally rising sea level (PARENT and OCCHIETTI, 1988). Since deglaciation, isostatic recovery has been very rapid. By 9,000 yr BP, about 85% of the coastal emergence had occurred (DIONNE, 1990). The mean rate of isostatic uplift has decreased from 3 cm year⁻¹ at 13,000 yr BP to less than 1 mm year⁻¹ today (DIONNE, 1988). Marine maximum depth of about 250 meters north of Montreal and about 55 meters south of Lake Champlain have been established (PARENT and OCCHIETTI, 1988). Isostatic rebound has lifted some of the associated marine deposits above sea level, while others remain submerged under the St. Lawrence River and its estuary.

The St. Lawrence River drains a basin of approximately 1.2×10^6 km² consisting largely of crystalline rocks of the Canadian Shield. The surficial cover of much of the area immediately bordering the Great Lakes and north and south of the St. Lawrence River valley is composed to a large extent of fine-grained sediments of the Champlain Sea. These are derived predominantly from ice-ground Precambrian material from the Canadian Shield ("rock flour"). Lithofacies of the Champlain Sea deposits have been described from boreholes in the Ottawa Valley (GADD, 1986). The lowest deposits are marine and consist of massive to weakly stratified blue-grey clays and silty clays which apparently were deposited at the time of deglaciation. Upper Champlain Sea horizons show a marked decrease in salinity as indicated by salinity-dependent foraminiferal assemblages (RODRIGUES and RICHARD, 1986) and range from clay to sand in texture. The top unit consists of rhythmically bedded couplets of grey, silty clays and red clays that are interpreted as deltaic deposits.

Seismic reflection surveys of the Upper St. Lawrence Estuary (PRAEG *et al.*, 1990) indicate accumulation of 200 meters or more of marine clays over glacial tills and bedrock. Most are seismically transparent deep water marine clays of Goldthwait age. These clays often lie under a thin cover of Recent sediments, but at some places outcrop on the channel floor (D'ANGLEJAN and BRISEBOIS, 1978).

MATERIALS AND METHODS

Sampling

Subaerially exposed deposits were sampled from three stratigraphic sections (Saint-Césaire, Spar-

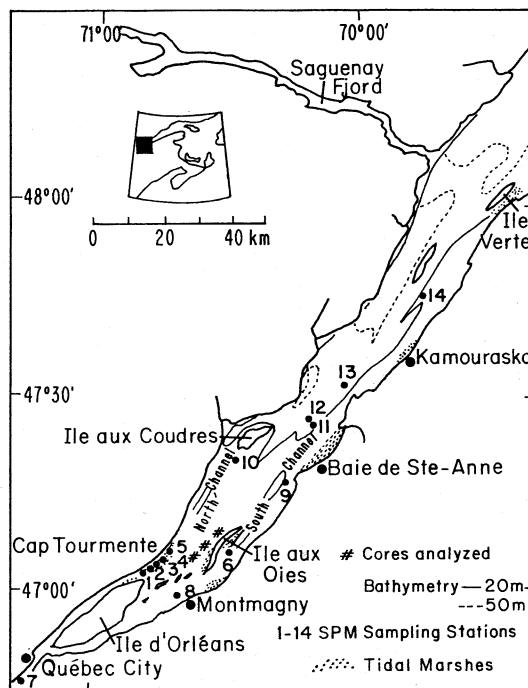


Figure 2. The Upper St. Lawrence Estuary: location of the core and suspended-sediment sampling stations.

rowhawk Point, Casselman) outcropping in the Central St. Lawrence Lowlands (Figure 1). Submerged deposits were collected by gravity coring in the Upper St. Lawrence Estuary (Figure 2). The core samples are identified as being of Goldthwait age on the basis of the sediment characteristic color (bluish-grey) and textural properties, including high plasticity and fine grain-size (more than 60% by weight of particles < 2 μ m). These properties make these sediments very different from modern estuarine deposits.

All sections and cores were subsampled at intervals of 5 to 10 cm. Suspended sediment samples were collected in the lower St. Lawrence River and in the turbidity maximum zone of the Upper St. Lawrence Estuary by continuous flow centrifugation.

Laboratory Analyses

Prior to size separation, the calcium carbonate in the sediment samples was dissolved (JACKSON, 1969) using a 1N sodium acetate buffer (82 g of sodium acetate and 27 mL of glacial acetic acid

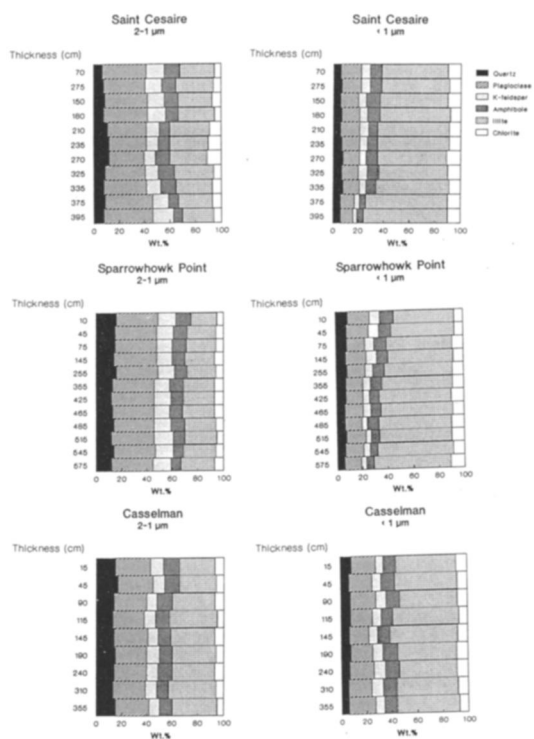


Figure 3. Semi-quantitative mineralogy of marine clay and colloid-size fractions from the Champlain Sea deposits.

per liter, adjusted to pH 5.0) and the suspension centrifuged until the supernatant liquid was clear. The residues, considered to represent the carbonate-free fraction were separated into a sand fraction ($> 62 \mu\text{m}$), a silt fraction ($2\text{--}62 \mu\text{m}$), a clay fraction ($1\text{--}2 \mu\text{m}$) and a colloidal fraction ($< 1 \mu\text{m}$) by wet sieving and by centrifugation, as described by HARRY *et al.* (1984). Due to the limited quantity of material available, the samples of SPM were not size-fractionated.

Aliquots of the clay and colloidal size fractions of the sediments as well as the bulk SPM were treated by the Dithionite-Citrate-Bicarbonate (DCB) procedure of MEHRA and JACKSON (1960) in order to remove amorphous oxides.

Using X-ray powder diffractometry, precise clay mineral concentrations that accurately reflect sample to sample variations can be determined by adding a 10% talc internal standard (HEATH and PISIAS, 1979). For the X-ray powder diffraction analyses, 100 mg of sample were dispersed

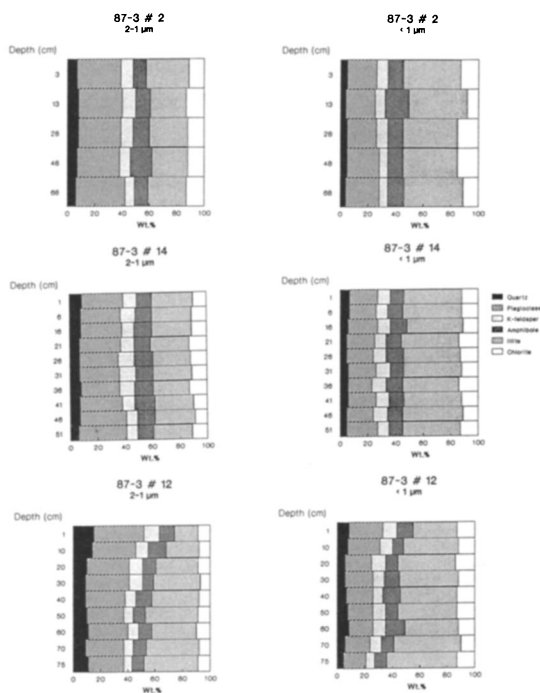


Figure 4. Semi-quantitative mineralogy of marine clay and colloid-size fractions from the Goldthwait Sea deposits.

in 5 mL of deionized distilled water. A similar suspension of talc (obtained from Alberene, Virginia and prepared by wet-grinding and Stoke's law settling) was also made. A homogenized mixture of 1.8 mL of clay suspension and 0.2 mL of talc suspension was transferred to a 15 mL test tube and stirred with a Deluxe mixer or a Branson ultrasonic cleaner. The suspension was then immediately poured onto a 37.5 mm \times 25 mm glass slide. No washings were applied to the test tube, as this might disturb the homogeneity of the suspension on the slide (KODAMA *et al.*, 1977). Consequently, a small loss (1–2 mg) of sample was unavoidable. Selected samples were heated at 550 °C for 1 hour to test for kaolinite. Other samples were glycolated overnight before X-ray analyses to test for smectite.

All samples were analyzed using a Siemens D 500 X-ray diffractometer at $1^\circ 2\theta$ per minute. $\text{CuK}\alpha$ radiation was generated using settings of 40 kV and 20 mA. Diffractogram peak areas were determined using the peak height times peak width at half height method (SEGALL *et al.*, 1987).

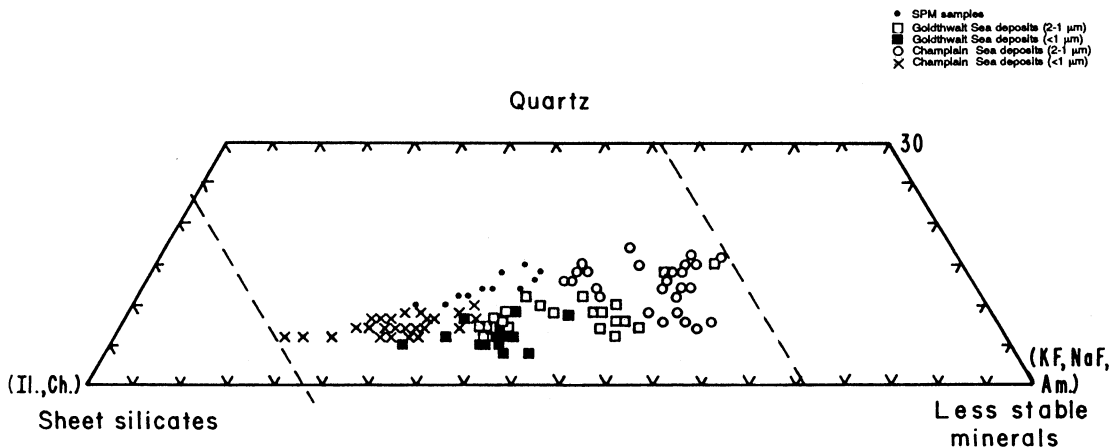


Figure 5. The triangular plot of the sum of the percentages of the phyllosilicates (illite and chlorite), the sum of percentages of clastic primary minerals relatively less stable in aqueous environment (plagioclase, K-feldspar, amphibole) and the percentage of quartz in clay and colloid-size fractions of the Champlain and of the Goldthwait Sea deposits and in the bulk suspended sediments of the St. Lawrence River and its Estuary.

The 10 Å, 7 Å, 8.4 Å, 3.34 Å, 3.19 Å and 3.25 Å peaks were used to identify illite, chlorite, amphibole, quartz, plagioclase and K-feldspar, respectively. No smectite or kaolinite was found. No attempt was made to resolve and quantify more complex mixed-layer clay mineral phases, minor amounts of which appear to be present in some samples.

To simplify processing, all peak areas were normalized to the area of the 9.3 Å peak of the 10% talc internal standard. Linear programming (HEATH and PISIAS, 1979; later modified by PISIAS, 1989 unpublished) was used to generate factors for converting talc-normalized peak areas to weight percentages. This procedure minimizes residuals (non(-)diffracting or poorly crystalline components) but its accuracy is untested. Although this procedure results in an average residual of about 35% for post-glacial sediments, other peak-area to weight conversion schemes (BISCAYE, 1965) generate even larger values. The percentages calculated for these samples are semi-quantitative and reflect only the relative abundances of identified minerals. Duplicate analyses show generally good reproducibility. Overall analytical precision is estimated to be $\pm 5\%$.

The major, minor and trace element chemistry of the bulk estuarine suspended sediments and a limited number of the clay and colloid-size frac-

tions of the exposed and submerged sediment samples were analyzed by X-ray fluorescence (Philips BW 1400). The accuracy was checked by analyses of two certified soil-samples, SO1 and SO2 from Canadian Centre for Mineral and Energy Technology (CANMET, 1979). The results were within the 95% confidence limits of the recommended values given for these two certified materials. Overall analytical precision was $\pm 2\%$ for the major and $\pm 5\%$ for the minor and trace elements.

RESULTS AND DISCUSSION

Mineralogy and Mineral Distribution

The mineralogical composition of the clay and colloidal size fractions from the exposed and submerged deposits are shown on Figures 3 and 4. The relative mineral abundances change with particle size in both the exposed and the submerged deposits. The proportion of phyllosilicates (illite and to a lesser extent chlorite) increases, and tectosilicates (plagioclase, K-feldspar and to a lesser extent quartz) decreases in the finer ($< 1 \mu\text{m}$) size fractions (Table 1 and Figure 5). Feldspars exceed quartz in both the 2-1 μm and the $< 1 \mu\text{m}$ size fractions. The presence of plagioclase feldspar and amphibole in the smaller size fraction indicates that the post-glacial sediments are mineralogi-

Table 1. Mean and range of mineral composition (in % by weight) in marine clay and colloid-size fractions from the Champlain and Goldthwait Sea deposits.

Location	2-1 μm						<1 μm					
	Q	PF	KF	A	I	C	Q	PF	KF	A	I	C
Exposed Deposits												
1. Saint Césaire (n = 22)												
Range	07-12	28-39	09-16	07-13	24-31	05-11	06-08	10-16	03-07	05-11	52-66	08-11
Mean	09	34	12	10	28	07	07	13	06	08	56	10
SD	1.64	3.11	2.19	1.85	2.00	1.90	0.75	1.67	1.29	1.80	4.33	0.78
2. Sparrowhawk Point (n = 24)												
Range	12-16	32-34	12-15	08-12	20-26	05-07	06-10	13-17	04-08	06-11	47-60	07-11
Mean	14	33	13	10	24	06	08	14	06	09	54	09
SD	1.40	0.55	0.95	1.19	1.61	0.72	1.08	1.44	1.50	1.50	3.83	1.15
3. Casselman (n = 18)												
Range	13-17	25-28	08-10	09-13	27-37	05-07	06-09	15-21	06-09	09-12	45-53	07-09
Mean	14	26	09	11	33	06	07	18	08	11	48	08
SD	1.17	1.07	0.74	1.20	3.31	0.79	0.94	1.69	0.96	0.83	2.70	0.74
Submerged Deposits												
1. Core 87-3 #2 (n = 10)												
Range	06-08	31-36	07-10	10-16	26-31	11-13	04-05	21-24	06-08	11-17	40-42	08-15
Mean	07	32	09	12	28	12	05	22	07	12	42	12
SD	0.75	1.85	1.02	2.23	1.83	0.75	0.49	1.26	0.89	2.33	1.36	2.65
2. Core 87-3 #14 (n = 20)												
Range	06-09	28-35	08-12	11-15	26-30	09-13	05-07	17-22	08-10	10-13	41-44	11-14
Mean	07	30	10	13	28	11	06	20	09	11	42	12
SD	0.80	2.24	1.41	1.14	1.08	1.22	0.75	1.27	0.77	0.94	0.89	1.02
3. Core 87-3 #12 (n = 18)												
Range	09-15	26-37	06-11	08-13	17-39	07-10	05-09	16-24	06-10	08-14	32-51	10-14
Mean	11	30	08	10	32	09	07	19	08	10	42	12
SD	2.08	3.14	1.57	1.47	6.84	0.83	1.37	2.49	1.26	2.01	5.22	1.07

Q = quartz; PF = plagioclase feldspar; KF = potassium feldspar; A = amphibole; I = illite; C = chlorite

n = number of samples analyzed

SD = Standard deviation

cally immature, as would be expected in mechanically ground "rock flour," derived mainly from the crystalline rocks of the Canadian Shield.

The <1 μm fractions from the Saint-Césaire and the Sparrowhawk Point sections and from core 87-3 #12 all exhibit a downward decrease in the percentages of the four primary minerals: plagioclase, K-feldspar, and, to a lesser extent, amphibole and quartz. A corresponding increase in illite content is also noted along these three profiles. As sample preparation and experimental conditions were identical, this decrease may be the result of post-depositional diagenetic alteration. Based on ^{14}C dating (RODRIGUES, 1988), the depth interval over which the decrease in primary minerals and the increase in illite are noted correspond to a time interval of about 600 years. Due

to isostatic rebound, these Champlain Sea clays have been lifted up to 200 m above the present sea level and have been exposed to subaerial weathering for the last 9,000 years. Phyllosilicates with a dioctahedral 2:1 layer structure are known to be more resistant to chemical weathering than feldspar and quartz (RUESLÄTTEN and JØRGENSEN, 1977; PEDERSTAD and JØRGENSEN, 1985). KONTA *et al.* (1970) found dioctahedral illite in the clay fraction from strongly weathered soils where all other primary minerals are absent. PEDERSTAD and JØRGENSEN (1985) also found an increase in dioctahedral illite and a decrease in quartz, K-feldspar, and plagioclase with depth in the fine fraction of the Norwegian post-glacial clays as a result of weathering. No attempt was made in this study to identify the exact nature of

the illite. Since weathering intensity depends on the surface area of the mineral particles in contact with the liquid phase, the effects of weathering are most easily observed in the colloid-size fractions. Similar vertical trends in the mineralogy were not found in the Casselman section and two of the estuary cores (87-3 # 2 and 87-3 # 14). The observed mineral distribution and the textural index (sand%/silt+clay%; RAMESH, 1991) remains constant throughout the Casselman section, suggesting that these sediments may all represent deep-water marine deposits with no indication of weathering. It appears that the extent and pattern of post-depositional alteration in the Central St. Lawrence Lowlands is strongly influenced by local factors and that no broad spatial trends exist.

Diffraction patterns obtained on material from the cores and from some samples in the subaerially exposed sections indicate a change with size in the intensity ratio of the 001 (14.2 Å) to the 002 (7.10 Å) reflections for chlorite. This ratio decreases in the <1 µm and the enhancement of the 002 (7.10 Å) reflection coincides with a marked reinforcement of the 004 (3.55 Å) reflection. This suggests an Fe increase in octahedral positions with decreasing size. It has been demonstrated that an increase in Fe or in other heavy metal causes weakening of the 001, 003, and 005 reflections relative to the 002 and 004 reflections (BROWN and BRINDLEY, 1980; MOORE and REYNOLDS, 1989). The results suggest the possibility that the relatively large Fe/Mg ratio in the Champlain beds is caused by particularly high percentages of Fe-rich chlorite. The results of this study do not preclude the formation of Fe-rich chlorite by digenesis.

No systematic regional differences in mineralogy seem to exist between the marine clays from the exposed (Champlain) and from the submerged (Goldthwait) deposits. However, analyses of the sediment core samples from the submerged deposits (Table 1) show a slight (2–5%) but significant increase in chlorite over the subaerially exposed sediments, both in the clay and in the colloid-size fractions. This suggests that the Appalachian sedimentary rocks or the soil horizons developed over the Appalachian bedrock, which are known to be enriched in chlorite (KODAMA, 1979), may have represented the dominant source for the submerged deposits in the estuary region. This source would have been active during the retreat of the Appalachian ice dome. Seismic profiling of the estuary provides evidence for sedi-

ment transport from the south at that time (PRAEG *et al.*, 1990).

The illite-to-chlorite ratio in the samples analyzed ranges between 2 and 5 in the submerged deposits of the estuary and between 3 and 7 in the exposed deposits of the Lowlands in clay and colloidal size fractions. KODAMA (1979: Figure 2) reported an average illite-to-chlorite ratio of 3 in the subsoils of the St. Lawrence Lowlands. The somewhat higher proportion of illite in the exposed deposits may well also reflect a closer proximity to sources in the Precambrian Shield, whose rocks contain abundant micas but a relatively small amount of chlorites (KODAMA, 1979).

In the fourteen samples of suspended sediment analyzed, the illite-to-chlorite ratio varies between 3 to 4. No conclusive trends are observed across the salt gradient at the head of the estuary, suggesting that flocculation exerts no sorting effect on the clay minerals. Since the mineralogical composition of the clay-size material in the post-glacial deposits is similar to that found in the bulk SPM (Tables 1 and 2), it appears that immature (both mineralogically and chemically) material continues to be supplied by the St. Lawrence River under the present climatic conditions and that the residence time of this material in soil profiles is too brief to produce any appreciable weathering transformation.

Sorting processes during erosion and transportation result in SPM which is coarser than the source. A decrease in illite content and an increase in primary minerals within the SPM as compared to the colloid-sizes of the exposed and submerged deposits (Tables 1 and 2) is in agreement with the previous observations (KRANCK, 1979). It suggests that the finest detrital products introduced by the St. Lawrence drainage system into the upper estuary are transported downstream toward the lower estuary and the Gulf of St. Lawrence on a time scale which is shorter than the slightly coarser particles. The latter tend to be retained within the estuary by the residual non-tidal circulation.

Chemical Composition

Table 3 summarizes the major, minor and trace element composition of the three sediment types studied. The data do not show any systematic variation with depth either in the exposed sections or in the cores. However, an examination of the chemical composition of the clay and colloid-size materials reveals small but significant differences in composition which are also apparent in

Table 2. Semi-quantitative mineralogy (in % by weight) of the bulk lower St. Lawrence River and its estuarine suspended sediments.

Sample* Number	Q	PF	KF	A	I	C	M _M	Ch _M
1	14	21	07	09	37	12	1.32	1.72
2	12	21	09	10	37	11	1.20	1.74
3	13	23	08	10	36	10	1.12	1.51
4	15	21	09	09	33	13	1.18	1.04
5	14	22	09	10	33	12	1.10	1.36
6	10	19	07	07	42	15	1.73	1.65
7	11	20	06	09	40	14	1.54	1.68
8	11	20	06	08	45	10	1.62	1.69
9	12	21	09	07	39	12	1.38	0.97
10	12	20	08	09	38	13	1.38	1.16
11	10	17	07	06	49	11	2.00	1.24
12	10	17	07	09	46	11	1.73	1.39
13	12	23	06	08	39	12	1.38	1.34
14	12	21	06	09	40	12	1.44	0.99
Range	10-15	17-23	06-09	06-10	33-49	10-15	1.10-2.0	0.97-1.74
Mean	12	20	07	09	40	12	1.44	1.39
SD	1.51	1.76	1.18	1.18	4.48	1.36	0.25	0.27

Q = quartz; PF = plagioclase feldspar; KF = potassium feldspar; A = amphibole; I = illite; C = chlorite

M_M = mineral maturity; Ch_M = chemical maturity; SD = standard deviation

*Sample numbers correspond to Figure 2

the mineralogical studies. For example, the depletion of Si, Na, and Ca in the colloid-size fraction reflects diminishing amounts of quartz and plagioclase. Similarly, enrichment in Al, Fe and Mg in the same fraction reflects an increasing abundance in clay minerals and Fe hydroxides. LORING and NOTA (1973) also reported change of major elemental composition with particle size for the coarser fractions of marine sediments from the Gulf of St. Lawrence. An increase of Fe/Mg ratio (by 0.3) in the colloid-size compared to the clay-size fractions may be due to an increase in Fe-enriched chlorite in that fraction.

Table 3 indicates that the clay and colloid-size fractions in the cores are significantly higher in Ca, Na, K and Mg and lower in Si, Ti, Al and Fe than are sediments from the exposed sites. Mobilization of these elements by soil solutions in the vadose zone may partly explain this difference. It has been reported that the near-surface zone in the Champlain Sea clays is moderately permeable, as a result of fracturing and other weathering effects (LAFLEUR and GIROUX, 1983). Thus Ca, Na and K could be partly removed from the feldspars and Mg from the amphibole or the chlorite by soil solutions while Si, Ti, Al and Fe are retained in the upper horizons of the exposed deposits.

The average Mn, Ni, Co and Cu concentrations

(Table 3) in the Champlain and Goldthwait Sea clays are considerably higher than in the samples of suspended sediments. The post-glacial deposits may therefore be a source of dissolved trace metals to the river.

Evidence of Mild Weathering

The mineral maturity (M_M) is the ratio of the sum of the more stable minerals to that of the less stable minerals in aqueous environments (KONTA, 1988), and therefore reflects the mechanical to chemical weathering ratio of sediments in a river basin. The mineral maturity of the St. Lawrence River and its estuarine SPM and of the sediment samples from the sections and cores were computed (Figure 5) from the X-ray data as the ratio of the sum of the percentages of the phyllosilicates, relatively more stable in aqueous environments, to the sum of percentages of the less stable primary minerals according to the formula:

$$M_M = \% (\text{illite} + \text{chlorite}) / \% (\text{plagioclase} + \text{K-feldspar} + \text{amphibole}).$$

The chemical maturity (Ch_M) is expressed by a simple ratio % Al₂O₃ : % (Na₂O₂ + MgO + CaO*) (KONTA, 1985), where CaO* is the amount of CaO incorporated in the silicate fraction of the rocks.

Table 3. Mean and range of elemental composition* (corrected to L.O.I.) of fine grained sediments from the St. Lawrence Lowlands.

Element	Exposed Deposits				Submerged Deposits				SPM	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
	2-1 n = 12	μm	<1 μm 12	<1 μm 12	2-1 μm 11	<1 μm 11	Bulk 14	Bulk 14		
SiO ₂	59.13 (1.94)	54.78- 62.57	53.97 (0.59)	52.56- 54.73	56.76 (0.75)	55.69- 58.29	53.37 (0.39)	52.68- 54.19	60.60 (2.29)	57.19- 63.79
TiO ₂	0.95 (0.07)	0.79- 1.03	0.92 (0.07)	0.80- 0.99	0.72 (0.02)	0.69- 0.75	0.76 (0.02)	0.74- 0.79	1.00 (0.06)	0.88- 1.11
Al ₂ O ₃	18.55 (0.57)	17.59- 19.40	20.70 (0.62)	19.34- 21.48	18.01 (0.50)	17.19- 18.56	19.84 (0.14)	19.59- 19.99	15.63 (0.38)	15.04- 16.36
Fe ₂ O ₃	8.56 (0.74)	7.06- 9.68	11.49 (0.78)	10.46- 13.06	7.66 (0.57)	6.84- 8.27	10.27 (0.1)	10.09- 10.43	7.80 (0.39)	7.13- 8.48
MnO	0.11 (0.01)	0.09- 0.12	0.13 (0.01)	0.10- 0.14	0.12 (0.01)	0.11- 0.13	0.13 (0.01)	0.12- 0.15	0.18 (0.02)	0.16- 0.24
MgO	3.73 (0.44)	3.18- 4.81	4.47 (0.27)	4.23- 5.14	4.54 (0.15)	4.20- 4.74	5.31 (0.1)	5.08- 5.49	3.13 (0.36)	2.42- 4.07
CaO	2.73 (0.59)	2.27- 4.49	2.34 (0.52)	1.85- 3.84	5.84 (0.78)	4.92- 7.27	4.03 (0.42)	3.26- 4.83	3.06 (0.32)	2.60- 3.54
Na ₂ O	2.12 (0.25)	1.75- 2.59	1.43 (0.26)	1.09- 2.12	2.67 (0.32)	2.22- 3.05	2.26 (0.24)	1.94- 2.62	5.50 (2.81)	2.38- 10.31
K ₂ O	3.46 (0.30)	3.12- 4.30	3.62 (1.40)	1.09- 4.88	3.89 (0.19)	3.13- 3.68	3.77 (0.13)	3.55- 3.93	2.73 (0.43)	2.27- 3.52
P ₂ O ₅	0.22 (0.04)	0.15- 0.27	0.24 (0.05)	0.13- 0.31	0.22 (0.02)	0.18- 0.23	0.23 (0.02)	0.19- 0.25	0.37 (0.04)	0.33- 0.48
V	112 (13.1)	91- 142	138 (13.7)	115- 161	92 (5.5)	79- 99	115 (5.7)	104- 124	—	—
Cr	219 (47.5)	140- 281	246 (44.2)	177- 295	227 (70.1)	121- 335	305 (86.8)	154- 379	—	—
Ni	63 (11.7)	46- 85	82 (9.2)	72- 99	71 (9.3)	56- 85	87 (10.9)	66- 99	44 (10.19)	33- 70
Ba	1,067 (266.8)	571- 1,340	10,009 (263.6)	495- 1244	787 (153.6)	554- 1038	704 (109.8)	540- 824	—	—
Co	40 (14.3)	17- 66	64 (9.4)	50- 79	38 (14.6)	17- 58	58 (15)	38- 82	16 (2.1)	13- 21
Cu	130 (69.1)	28- 229	150 (67.4)	15- 215	73 (58.73)	10- 170	83 (57.4)	14- 182	42 (12.1)	29- 77
Pb	37 (8.9)	25- 52	50 (14.8)	30- 71	28 (9.1)	18- 52	33 (4.6)	27- 42	—	—
Zn	142 (28.3)	102- 192	238 (205.1)	132- 907	102 (13.1)	79- 115	136 (5.6)	127- 147	188 (34.7)	131- 240

*Major element analyses are given in wt. %; minor element analyses in μg/g; L.O.I. = loss of ignition
n = number of samples analyzed; standard deviation given in parentheses

The Ch_M reflects the intensity of chemical weathering in a river basin.

Tables 2 and 4 present the computed values of M_M and Ch_M for the SPM, and for the samples from the exposed and from the submerged deposits. As might be expected, M_M and Ch_M increase in the fine-grained (< 1 μm) fractions which have a larger surface area. In the Saint-Césaire, and Sparrowhawk Point sections and in core 87-3

12, M_M and Ch_M increase with depth in the colloid-size fractions. The M_M increases from 1.94 to 4.22 at Saint-Césaire; from 1.50 to 3.09 at Sparrowhawk Point, and from 0.98 to 2.06 in Core 87-3 # 12. The Ch_M increases from 2.24 to 2.81; from 2.26 to 2.74, and from 1.70 to 1.76, respectively, for the two sections and the core. The downward increase in both M_M and Ch_M in the colloid-size fraction supports the interpretation, already sug-

Table 4. Mean mineral and chemical maturity in marine clay and colloid-size fractions from the Champlain and Goldthwait Sea deposits.

Location	M_M		Ch_M	
	2-1 μm		<1 μm	
	n =			
	56	23	56	23
Exposed Deposits				
1. Saint-Césaire	0.64 (0.12)	2.25 (0.16)	2.52 (0.71)	2.61 (0.23)
2. Sparrowhawk Point	0.53 (0.04)	2.18 (0.11)	2.25 (0.46)	2.53 (0.15)
3. Casselman	0.86 (0.10)	2.09 (0.25)	1.56 (0.17)	2.45 (0.37)
Submerged Deposits				
1. Core 87-3 #2	0.76 (0.04)	1.30 (0.13)	1.31 (0.09)	1.69 (0.12)
2. Core 87-3 #14	0.74 (0.04)	1.45 (0.05)	1.37 (0.06)	1.74 (0.04)
3. Core 87-3 #12	0.85 (0.22)	1.48 (0.05)	1.46 (0.28)	1.73 (0.03)

n = number of samples analyzed; standard deviation given in parentheses

M_M = mineral maturity; Ch_M = chemical maturity

gested by the mineral concentration profiles, that mild weathering may have taken place since deposition. PEDERSTAD and JØRGENSEN (1985) have demonstrated similar changes due to weathering in Norwegian post-glacial clays. These clays were deposited in marine or brackish environments, similar to those of the Champlain Sea deposits, immediately after glacial retreat and were subsequently elevated above sea level by isostatic readjustment of the land surface.

Table 5 gives the average M_M and Ch_M in post-glacial sediments of the St. Lawrence Lowlands and in sediments from other major world rivers (KONTA, 1985, 1988). The St. Lawrence post-glacial sediments are among the lowest values, indicating that these sediments are mineralogically as well as chemically immature when compared to other large river basins. Both the Ch_M and the M_M of suspended sediments in rivers depend on several factors: climate, relief, geology of the drainage basin, source of the sediments and vegetation. However, the values shown in Table 5 suggest that climate is the major controlling factor. Tropical and subtropical rivers (Niger, Orinoco, Orange, Parana) contain suspended sediments having higher M_M and Ch_M . The lower values of M_M and Ch_M are typical of the suspended inorganic sediments in rivers draining cold or warm

Table 5. Mineral and chemical maturity in the St. Lawrence Lowland sediments and other major rivers of the world.

River	M_M	Ch_M
St. Lawrence Lowlands*		
a) Exposed Deposits	1.39	2.35
b) Submerged Deposits	1.08	1.57
c) St. Lawrence River & Estuarine SPM	1.44	1.39
Mackenzie	3.22	2.50
Orinoco	17.84	4.80
Parana	5.91	5.30
Nile	1.84	1.20
Niger	34.15	5.50
Orange	12.64	1.60
Indus	3.71	1.50
Ganges	6.88	1.30
Brahmaputra	2.75	2.60

* Average values from present study

For other river basins data were computed from KONTA (1985, 1988)

M_M = mineral maturity; Ch_M = chemical maturity

arid regions (St. Lawrence, Mackenzie, Nile), where rates of erosion are relatively high.

Another measure of the degree of weathering can be obtained by calculation of the chemical index of alteration (CIA) using molecular proportions (NESBITT and YOUNG, 1982).

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$$

where CaO^* is the amount of CaO incorporated in the silicate fraction of the rock. The index is a measure of the percentage of Al_2O_3 versus all labile oxides in the analyzed sample. Typical values of the index are 0 for diopside, 50 for unaltered albite, anorthite and K-feldspars, 75 for idealized muscovite, between 75 and 85 for illite and montmorillonites and beidellites, and very close to 100 for kaolinite and chlorite. Fresh basalts have values between about 30 and 45 and granites and granodiorites values ranging between 45 and 55.

To facilitate the interpretation of the CIA values obtained from the clay and colloid-size fractions of the exposed and submerged deposits, values were also calculated for a variety of other rocks and sediments (Figure 6). Chemical analyses of the clay and the colloid-size portion of the 24 Champlain Sea exposed deposits yielded CIA values ranging from 65 to 71 and from 69 to 85, respectively. These values are higher than those obtained from the average Canadian Precambrian Shield rocks (CIA value of 52; computed from SHAW *et al.*, 1967). CIA for the 22 Goldthwait Sea

sediment samples analyzed ranges from 56 to 63 and from 63 to 69, for the clay and colloid-size fractions, respectively. These values are comparable to the CIA for Pleistocene glacial clays (between 60 and 65) computed from CHURCH (1967) and YOUNG (1981), and slightly higher than the average value for the Shield. The relatively higher CIA values for the exposed sediments as compared to those which have remained permanently submerged in the estuary further suggests the possibility of removal of labile minerals (e.g., feldspars) by ground water. The lower St. Lawrence River and its estuarine SPM gave CIA values in the 51 to 64 range, close to the range of values obtained from the Goldthwait Sea clay-size sediments.

SUMMARY AND CONCLUSIONS

This paper presents the first comprehensive investigation of the geochemistry and mineralogy of the fine-grained post-glacial marine clays in the St. Lawrence Lowlands, and the significance of these deposits as sources to the suspended load of the St. Lawrence River Basin. Previous studies have considered the bulk chemistry as well as the amorphous and mineral contents of the marine clays in the perspective of their mechanical properties, not in terms of their geochemical contributions to fluvial input into the ocean. The present one addresses the question of the relationship between size and composition. An improved knowledge of the quantitative mineralogy of these marine deposits and of their degree of maturity is obtained. Some evidence of incipient weathering alteration is provided. The implication is that fine-grained sediments which are the results of glacial processes are far from being geochemically inert, in spite of the low rate of chemical weathering generally associated with high latitudes.

Grain-size exerts the primary control on the mineralogy of the fine-grained post-glacial marine sediments. Feldspar and quartz are abundant in the clay-size, while illite and chlorite are predominant in the colloid-size fraction. There is no significant regional variation in the mineralogy of the post-glacial sediments examined. Clay mineral content generally corresponds with bedrock lithology of the source area; fine clays from the exposed St. Lawrence Lowlands sections tend to be richer in illite, while those from the estuary closer to chloritic Appalachian sources are richer in chlorite.

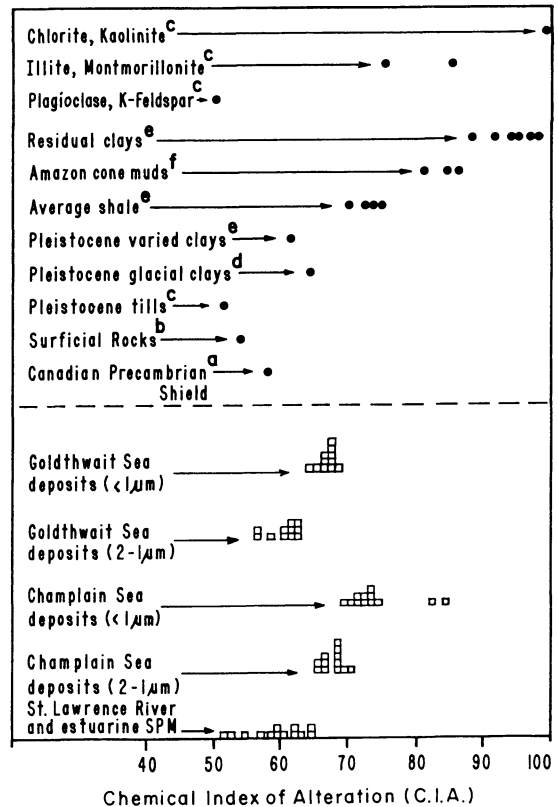


Figure 6. Chemical index of alteration (CIA) for clay and colloid-size fractions of Champlain and Goldthwait Sea deposits and various other rocks and sediments. Each square in the lower part of the diagram represents a single chemical analysis. Dots in the upper part of the diagram are either individual analyses or averages. Source of data: (a) SHAW *et al.*, 1967; (b) MARTIN and MEYBECK (1979); (c) NESBITT and YOUNG (1982); (d) CHURCH (1967); (e) YOUNG (1981); (f) CHANDLER *et al.* (1969).

In three of the six profiles studied, vertical trends in the mineral maturity (M_M) and chemical maturity (Ch_M), as well as changes in the mineralogy and chemical composition of the colloid-size fraction, support the possibility of mild weathering (dissolution of plagioclase, K-feldspar, and to a lesser extent, amphibole and quartz). The St. Lawrence Lowland sediments contain very low M_M and Ch_M values when compared to some of the major rivers of the world. This indicates that immature (both mineralogically and chemically) material is still being supplied by the St. Lawrence River under the present climatic conditions

and that weathering in soil profiles is insignificant. The Chemical Index of Alteration (CIA) values, on the other hand, suggest a higher degree of alteration of the exposed deposits as compared to those which have remained permanently submerged.

ACKNOWLEDGEMENTS

We thank Professors Reinhard Hesse and Alfonso Mucci for critically reviewing the manuscript. We are grateful to professor N.G. Piasias for providing the linear program for the quantitative estimation of minerals. Financial support in the form of a scholarship was provided to R. Ramesh by the Association of Universities and Colleges of Canada and by the Department of Science and Technology, Government of India. This study was also supported by a grant to the second author from the Natural Sciences and Engineering Research Council of Canada (NSERCC).

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