The Canadian Mineralogist
Vol. 36, pp. 1625-1636 (1998)

MINERALOGY, GRAIN-SIZE DISTRIBUTION AND GEOTECHNICAL BEHAVIOR OF CHAMPLAIN CLAY CORE SAMPLES, QUEBEC

RICHARD W. BERRY[1]

Department of Geological Sciences, San Diego State University, San Diego, California 92182, U.S.A.

J. KENNETH TORRANCE[1]

Department of Geography and Environmental Studies, Carleton University, Ottawa, Ontario K1S 5B6

ABSTRACT

Samples of Champlain Sea sediment from St-Barnabé, Quebec, near the Canadian Shield contact of the Champlain Sea basin, and from Henryville, Quebec, near the Appalachian Mountains contact, are dominated by the tectosilicates (47–82%). At Henryville, quartz and plagioclase are dominant, with lesser K-feldspar; among the phyllosilicates, the 4–0.5 μm fraction contains, in decreasing order, chlorite, illite, and expandable clay, except in the near-surface weathered zone, where the expandable clay is in greatest quantity. In the <0.5 μm fraction, expandable clay also dominates in the surface and basal zones of the sediment. At St-Barnabé, plagioclase is dominant, with lesser amounts of quartz and K-feldspar; the phyllosilicate component of the 4–0.5 μm fraction is dominated by illite, with much lower proportions of chlorite and expandable clay at all depths, whereas in the <0.5 μm fraction, the proportion of expandable clay increases relative to illite and chlorite, although it generally is not dominant. The sensitivity of the sediment decreases as the relative abundance of expandable clays increases. Oxide concentrations are low, on the order of 1% of the total sample; although relatively more abundant in the smaller size-fractions, the quantity increases at a lesser rate than the surface area. The relatively small amount of oxides present suggests that, at these levels, they probably affect soil behavior by a cementing action that is analogous to a "spot welding" process at interparticle contacts.

Keywords: Champlain Sea, Leda clay, mineralogy, geotechnical behavior, size fractionation, tectosilicates, expandable clays, oxide minerals, Quebec.

SOMMAIRE

Les échantillons de sédiment déposés dans la mer Champlain à St-Barnabé, Québec, près de la bordure de ce bassin avec le Bouclier Canadien, et à Henryville, Québec, près de sa bordure avec la chaîne des Appalaches, contiennent surtout des tectosilicates (47–82%). A Henryville, quartz et plagioclase prédominent, et le feldspath potassique est accessoire, tandis que les phyllosilicates présents dans la fraction 4–0.5 μm sont, en ordre décroissant d'importance, chlorite, illite, et argile gonflante, sauf dans la couche lessivée près de la surface, où l'argile gonflante est la plus importante. Dans la fraction <0.5 μm, l'argile gonflante est encore dominante dans la couche de surface et à la base de la séquence de sédiments. A St-Barnabé, le plagioclase est dominant, le quartz et le feldspath potassique étant accessoires; parmi les phyllosilicates dans la fraction 4–0.5 μm, l'illite est dominante par rapport à la chlorite et l'argile gonflante à toutes les profondeurs, tandis que dans la fraction <0.5 μm, la proportion d'argile gonflante augmente par rapport à l'illite et à la chlorite, quoiqu'elle n'est pas dominante en général. La sensibilité du sédiment diminue à mesure qu'augmente la proportion d'argile gonflante. La concentration d'oxydes est faible, de l'ordre de 1% de l'échantillon. Quoiqu'en général plus abondant dans les fractions à granulométrie plus fine, la quantité augmente moins rapidement que l'aire de la surface des sédiments. La proportion relativement faible des oxydes fait penser qu'ils agissent comme ciment dans les sols dérivés de ces sédiments, d'un façon analogue à une soudure ponctuelle aux contacts entre particules.

(Traduit par la Rédaction)

Mots-clés: mer Champlain, argile Leda, minéralogie, comportement géotechnique, fractionnement par taille de grains, tectosilicates, argiles gonflantes, oxydes, Québec.

---

[1] *E-mail addresses*: rberry@geology.sdsu.edu, ken_torrance@carleton.ca

INTRODUCTION

Fine-grained products of late Pleistocene glacial erosion were deposited in the Champlain Sea, a marine invasion of the modern St. Lawrence and Ottawa River valleys, and extending south into the Lake Champlain basin (Gadd 1962, 1986). The exposed marine sediments of the St. Lawrence Basin, for which the common collective term is Leda clay, but which are more accurately designated by the names of individual subbasins (Goldthwait: Lower St. Lawrence beyond Quebec City, Laflamme: Saguenay, and Champlain: inland from Quebec City), are prone to slope failure and may exhibit quick-clay behavior, resulting in large landslides. This susceptibility to failure leads to great interest by engineers and land-use planners. The mineralogy, grain-size distribution, pore-water chemistry and geotechnical behavior of Champlain Sea deposits have been studied, but a thorough mineralogical investigation, with fractionation of the sediment into multiple class-sizes and consideration of mineralogical changes through the weathering crust, has not previously been conducted in parallel with the other factors. The purpose of this study is to link the results of detailed mineralogical analyses to geochemical and geotechnical factors in order to obtain further insight into the controls of variations in sensitivity of these marine sediments. Torrance's (1983) preferred definition of quick clay as exhibiting a sensitivity greater than 30 and a remolded strength below 0.5 kPa (*i.e.*, liquid behavior) is adopted.

BACKGROUND INFORMATION

Papers by Torrance (1983, 1988, 1990), Locat *et al.* (1984) and Locat (1996) contain the most comprehensive reviews of mineralogical information and hypotheses pertaining to quick clay in general, and the St. Lawrence Basin deposits in particular. They also contain extensive references (not duplicated here) to other related work on the behavior of these sediments. Whereas the suite of minerals that is present in the St. Lawrence Basin marine clays is well documented by these extensive references, and the relative abundances

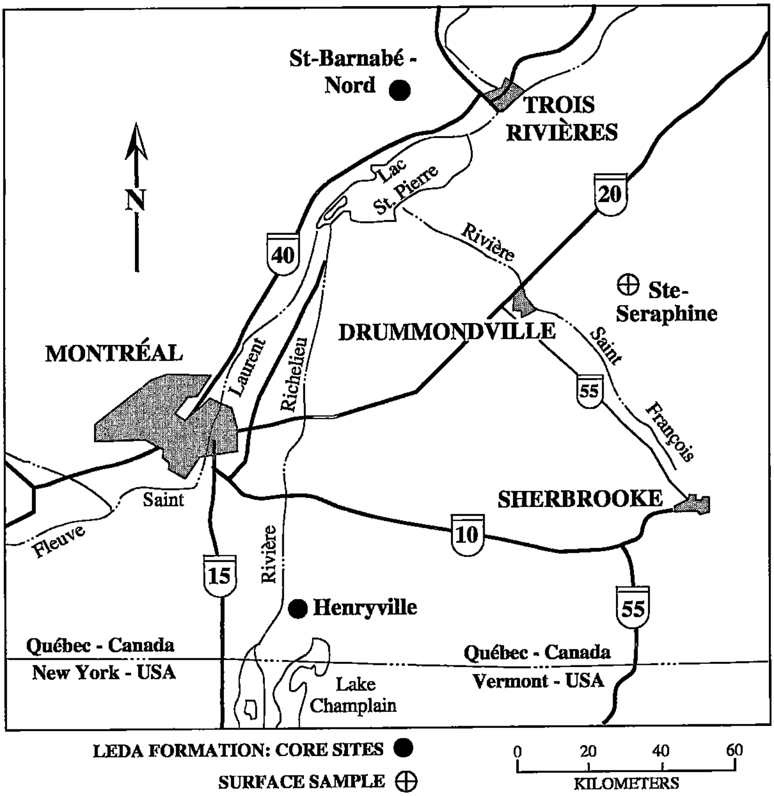

FIG. 1. Map showing the location of St-Barnabé, Ste-Séraphine and Henryville, in eastern Quebec.

and range of abundances of the primary minerals are generally reliable (feldspars > quartz > amphiboles), as is the relative amount of primary minerals to phyllosilicates, the use of an extremely aggressive chemical procedure to extract and quantify "amorphous" minerals invalidates the results concerning phyllosilicates and oxide minerals (Torrance 1995).

An extensive set of mineralogical, textural, geotechnical and chemical data serves as the basis for this paper. The data were obtained by analysis of undisturbed core samples taken from Henryville and St-Barnabé and a near-surface grab sample collected from the bottom of a newly constructed ditch at Ste-Séraphine, all in the province of Quebec. Figure 1 shows site locations. At Henryville, the core samples represent the complete depth-sequence. At St-Barnabé, the core samples represent only the top few meters of a very deep deposit. No large landslides have occurred near the Henryville site (topographic reasons), whereas the St-Barnabé samples come from an undisturbed site in an area with intense prehistoric landslide activity (Karrow 1972).

PROCEDURES

Core-sampling intervals were selected on the basis of the drill logs in order that the samples encompass a range of sensitivity. Core segments and sampling positions are shown in Table 1. Although samples with high and low sensitivity were analyzed, sections of the cores with the highest sensitivity were not recognized until too late in the project to adjust the sampling interval. Missing the zones of highest sensitivity was unfortunate, but does not affect the interpretation of the results.

Samples of approximately 0.25 kg were dispersed in deionized water and size-fractionated utilizing Stokes's Law into the following fractions: >16, 16–4, 4–2, 2–0.5 and <0.5 μm. Each sample was analyzed for proportions of quartz, plagioclase and K-feldspar utilizing standard-addition techniques and X-ray diffraction. Each size fraction of each sample was analyzed, semiquantitatively, for clay mineral content (illite, chlorite, kaolinite and expandable clays). No attempt was made to estimate the relative abundances of expandable clay minerals, but it became clear that smectite-group minerals, particularly montmorillonite, predominate. Trends in clay-mineral abundance were calculated in terms of Clay Index Numbers (CINs) (Berry 1987), which are related to peak intensities (by area) of 10 Å (glycolated) for illite, 14 Å (heat-treated) for chlorite, 7 Å (heat-treated) for kaolinite, and the difference in intensities of the 10 Å (glycolated) and the 10 Å (heat-treated) peaks for expandable clay minerals (see Appendix). Although actual abundances of individual clay minerals were not determined, increases and decreases in relative abundances of constituent clay minerals are accurately measured. In this way, changes in clay mineralogy may be compared with changes in other parameters.

TABLE 1. SAMPLING DEPTHS AND INTERVALS FOR HENRYVILLE AND ST-BARNABÉ CORES

Henryville core			St-Barnabé core		
1	2	3	1	2	3
1.00 – 1.10 m	Top	1 m	1.02 – 1.15 m	Top	1 m
2.80 – 2.90 m	Bottom	3 m	3.02 – 3.17 m	Top	3 m
5.05 – 5.15 m	Top	5 m	6.05 – 6.22 m	Top	6 m
7.02 – 7.15 m	Top	7 m	9.00 – 9.15 m	Top	9 m
			11.20 – 11.37 m	Top	11 m

Column headings: 1: Depth range of core segment, 2: Aliquot position, 3: Sample depth (for purposes of plotting).

The mineralogy of the iron and aluminum oxides was investigated by the use of dithionite–citrate (DC) and acid ammonium oxalate (AAO) extractions (Sheldrick 1984) on all the size fractions smaller than 4 μm, and by Mössbauer spectroscopic investigations of separate core samples (not segregated by size) from 1 and 9.7 m depths at St-Barnabé and from 1 and 4 m depths at Henryville.

Details concerning some of the analytical procedures performed on the core samples are presented in a Laboratory Technique Report (Berry 1987). The following procedures are included in the report and summarized in the Appendix, adapted from that report: 1) Size separation of the samples, 2) X-ray analysis for clay minerals, 3) calculation of CIN numbers for clay minerals, 4) X-ray analysis for quartz, plagioclase and K-feldspar, and 5) standard-addition techniques for reduction of data concerning the tectosilicates.

RESULTS AND DISCUSSION

Grain size and sorting

The median phi grain-size of the core samples ranges from 8.0 phi to 9.3 phi (3.9 to 1.62 μm), with Henryville being slightly finer than St-Barnabé material. The median phi grain size for the Ste-Séraphine sample is 6.0 phi (15.6 μm). Phi sorting and median grain-size values for all samples are presented in Table 2. Phi sorting varies from 1.85 to 4.15. The cumulative weight percents for the various size-fractions of each sample are presented in Table 3. These samples have their median grain-size in the coarse clay to fine silt range. The somewhat finer grain-size and better sorting at Henryville compared to St-Barnabé probably reflect the more distal location of Henryville relative to the retreating Laurentide ice sheets, which contributed so greatly to the sediments.

TABLE 2. MEDIAN GRAIN-SIZE AND SORTING, HENRYVILLE, ST-BARNABÉ AND STE-SÉRAPHINE SAMPLES

	Henryville			St-Barnabé			Ste-Séraphine		
1	2	3	4	2	3	4	2	3	4
1	1.62	9.3	3.05	2.24	8.8	3.25	15.6	6.0	6.0
3	1.97	9.0	3.25	3.40	8.2	3.75			
5	1.62	9.3	2.35						
6				3.40	8.2	3.45			
7	2.75	8.5	1.85						
9				3.90	8.0	4.15			
11				3.40	8.2	3.60			

Column headings: 1: Sample depth, in m, 2: Median grain-size (µm), 3: Median grain-size (ϕ), 4: ϕ sorting.

TABLE 3. SIZE FRACTIONS OF THE SAMPLES

Depth (m)	>16 µm	16–4 µm	4–2 µm	2–0.5 µm	<0.5 µm
			St-Barnabé core		
1	17.9	18.3	16.3	21.6	25.9
3	29.2	18.4	13.4	18.8	20.2
6	30.0	17.7	12.2	20.1	20.0
9	38.0	11.8	15.3	16.4	18.4
11	36.5	12.0	14.3	19.5	17.7
			Henryville core		
1	12.0	19.0	14.0	23.0	32.0
3	16.0	18.0	16.0	23.0	27.0
5	1.0	8.0	35.0	26.0	30.0
7	0.9	28.9	36.5	19.2	14.6
			Ste-Séraphine		
Surface	50.7	18.3	10.0	10.6	10.4

Non-clay silicate minerals

In agreement with Locat (1996) and others (Torrance 1988), we find that the tectosilicate minerals (principally quartz, K-feldspar and plagioclase) dominate the Champlain Sea sediments. Only the sample taken at five meters below the surface from the Henryville core contains less than 50 wt.% tectosilicates (47%). Other samples contain as much as 82% tectosilicates by weight. Table 4 presents the distribution of tectosilicates in samples from the Henryville and St-Barnabé cores and in the Ste-Séraphine grab sample, as well as the details of the variations in mineral proportions. When broken down into relative abundances of individual minerals, quartz and plagioclase are present in equal and dominant amounts in the Henryville core samples, whereas plagioclase dominates in the St-Barnabé samples. Amphibole was found in trace amounts (<2%) in all samples except the one meter (weathered) sample from the Henryville core.

TABLE 4. PROPORTION OF TECTOSILICATE MINERALS

Depth (m)	K-feldspar	Plagioclase	Quartz	Total
		St-Barnabé core		
1	13	29	17	59
3	8	40	16	64
6	15	43	24	82
9	22	38	16	76
11	18	23	23	64
		Henryville core		
1	3	23	26	52
3	5	29	31	65
5	3	23	21	47
7	3	30	31	64
		Ste-Séraphine		
Surface	7	14	60	81

The proportion of the minerals is expressed in wt.%.

Tectosilicates heavily dominate the >4 µm size-fractions of all samples; the 2–4 µm size-fraction contains an approximately equal mixture of clay minerals and tectosilicates, whereas clay minerals heavily dominate the <2 µm size-fractions. In total, clay minerals make up a minority fraction of the constituent mineral suite. The proportion of the tectosilicates varies only slightly with depth in both the Henryville and the St-Barnabé cores. Between-location variability in mode, grain size, and relative abundances of minerals are attributed to differences in source area. The proximity of Henryville to the Appalachian Belt, with its relatively phyllosilicate-rich sedimentary and metamorphic rocks, allows for a finer-grained Appalachian-derived sediment to mix with the dominantly igneous Canadian Shield source. The Canadian Shield is essentially the exclusive source of the minerals at St-Barnabé.

Clay minerals

The CINs for the size fractions of all samples are presented in Table 5. Clay minerals do not occur in significant quantities in size fractions greater than 4 µm in any sample and will not be discussed.

The St-Barnabé core samples show little variation in clay-mineral assemblage with depth in the 4–2 µm (Fig. 2a, Table 5), and 2–0.5 µm size-fractions (Table 5), which are similar. Illite clearly dominates over chlorite and expandable clay minerals in the 4–0.5 µm size fractions at all depths. Chlorite and expandable clay minerals (chiefly montmorillonite) are present in approximately equal, but minor, amounts in the 4–0.5 μm size-fractions at all depths. The clay-mineral composition of the <0.5 μm fractions at St-Barnabé varies greatly with depth (Fig. 2b, Table 5). No clay mineral dominates at all depths of this finest size-fraction, but illite remains generally more abundant than chlorite and expandable clay minerals. In general, where the abundance of illite increases, the abundance of expandable clay minerals (principally montmorillonite) decreases, and *vice versa.*

The Henryville core samples show little variation in clay-mineral assemblage with depth in the 4–2 μm (Fig. 3a, Table 5), and 2–0.5 μm (Table 5) size-fractions below one meter. These size fractions are similar. Below one meter, chlorite dominates the clay mineral suite of these fractions, with illite only slightly less abundant; expandable clay minerals (principally montmorillonite) are present in minor amounts in all samples. In the sample taken at one meter, the 4–2 and 2–0.5 μm size-fractions are dominated by expandable clay minerals, with concomitantly lesser amounts of illite and chlorite. Notations on the drill logs related to color and consistency of the recovered material suggest that materials at this depth in the Henryville core are at the bottom of the modern soil zone and have experienced significant alteration by weathering. Differences in clay mineralogy of the 4–0.5 μm size-fraction between the sample taken at a depth of one meter and the rest of the core are consistent with such weathering. The assemblage of the clay minerals of the <0.5 μm fractions at Henryville shows a great deal of variation with depth (Fig. 3b, Table 5). No clay mineral dominates at all depths of this finest size-fraction. Interestingly, expandable clays dominate toward the surface and the base of the deposit, and illite and chlorite dominate through the middle portion.

Differences in the relative abundance of illite and chlorite in the 4–0.5 μm fractions of the Henryville and St-Barnabé core samples probably reflect sources of the sediment. The St-Barnabé samples are dominated by

TABLE 5. CIN VALUES FOR CLAY MINERALS

1	2	Exp	Ill	Chl	Kln	1	Exp	Ill	Chl	Kln
		St-Barnabé					Henryville			
1	>16	0	33	67	0	1	0	100	0	0
	16–4	5	92	3	0		51	23	26	0
	4–2	18	72	10	0		58	15	27	0
	2–0.5	31	59	10	0		88.3	8.3	3.3	0
	<0.5	33	54	13	<1		55	36	9	0
3	>16	0	33	67	0	3	0	27	73	0
	16–4	5	71	24	0		4	53	32	9 ± 5
	4–2	14	69	13	4 ± 2		17	40	43	0
	2–0.5	14	63.5	22.5	0		18	52	30	0
	<0.5	0	62	25	13 ± 6		22	47	31	0
6	>16	0	100	0	0	5	0	100	0	0
	16–4	0	85	15	0		19	29	45	7 ± 3
	4–2	4	81	9	6 ± 3		15	34	51	0
	2–0.5	9	72	11	7 ± 4		10	45	45	0
	<0.5	48	30	15	7 ± 3		12	49	39	0
9	>16	0	44	56	0	7	0	0	100	0
	16–4	22	64	14	0		20	26	54	0
	4–2	3	76	21	0		5	37	56	2 ± 1
	2–0.5	9	73	18	0		16	43	41	0
	<0.5	27	44	29	0		61	30	9	0
								Ste-Séraphine		
11	>16	0	100	0	0	Surf.	0	27	73	0
	16–4	15	77	8	0		2	45	53	0
	4–2	8	71	21	0		2	47	45	6 ± 3
	2–0.5	12	74	14	0		18	37	45	0
	<0.5	15	69	16	0		26	40	34	0

Column headings: 1: Depth, in m, 2: Size fraction, in μm, Exp: expandables, Ill: Illite, Chl: Chlorite, Kln: Kaolinite.

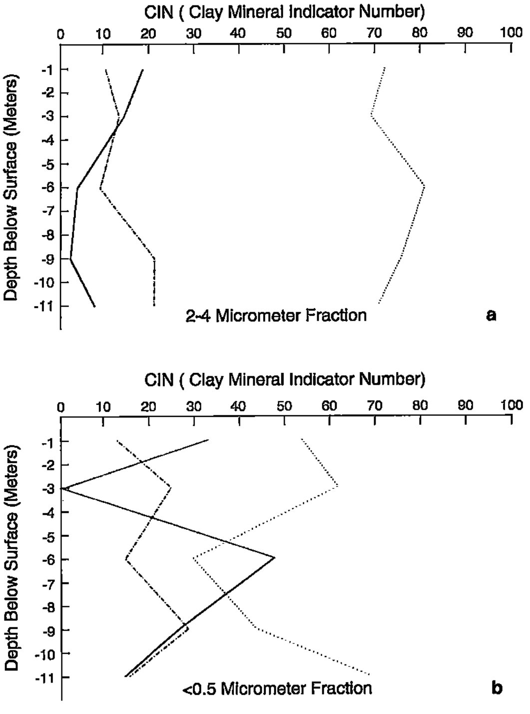

FIG. 2. Variations in clay mineralogy with depth at St-Barnabé in a) the 2–4 μm size fraction, and b) the 0.5 μm size fraction. Proportions of the phyllosilicates are shown as follows: ________ expandable clay, ... illite, _._._._._. chlorite.

illite (mica), and show little variation in clay minerals of the 2–4 μm size fraction with depth. Except at one meter below the surface (where weathering is an important factor), expandable clays are the least abundant constituent. The clay mineralogy of the St-Barnabé core reflects a Canadian Shield, glacially derived, source of sediment. In comparison, the 4–2 μm fraction of the Henryville core samples shows chlorite as a dominant mineral and less illite. Chlorite is equal to or less than illite in the 2–0.5 μm fraction. At Henryville, the clay minerals present in the sample at 1 meter depth reflect weathering more than sediment source, with expandable clays dominating in all the <4 μm size-fractions. Aside from the previously noted drill-log indications of soil and weathering at that depth, the uniform dominance by expandable clays in all fine fractions is more typical of an *in situ* origin of the suite of clay minerals. Were sediment source a major control on the suite of clay minerals at the one meter depth, one would find differences in clay mineralogy from one size fraction to another, related to sorting by particle size during transport from a distant source-area. As with the grain-size attributes, the more distal location (100 km) of Henryville relative to the Canadian Shield and its closer proximity (30 km) to the Appalachian Mountains affects the clay-mineral assemblage in a manner that reflects an Appalachian sediment source in addition to the dominant Canadian Shield source.

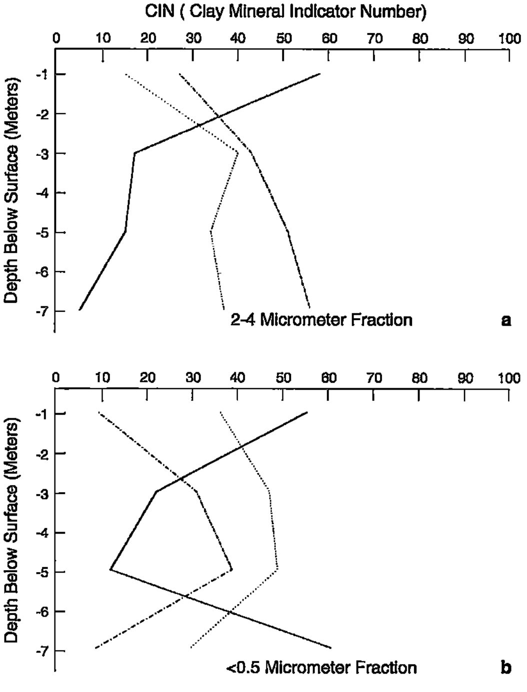

FIG. 3. Variations in clay mineralogy with depth at Henryville in a) the 2–4 μm size fraction, and b) the 0.5 μm size fraction. Proportions of the phyllosilicates are shown as follows: ________ expandable clay, ... illite, _._._._. chlorite.

The <0.5 μm size-fractions of both the Henryville and St-Barnabé core samples show a high degree of variability in clay-mineral assemblage with depth below surface. Given the small quantity of this size fraction in all samples, and the increased susceptibility of fine-grained minerals to alteration (by diagenesis or reaction with groundwater), definitive attribution of these variations to any particular cause is difficult. The greater amount of expandable clay minerals in the <0.5 μm size fraction at the 7 meter depth of the Henryville core may reflect a greater importance of a fine-grained, weathered (soil) Appalachian Mountains source for the sediment at that depth.

The 4–2 μm size fraction of the Ste-Séraphine ditch-bottom sample (a shallow-water sediment, about 15 km from the Appalachian front) contains essentially equal amounts of illite and chlorite (CINs of 47 and 45, respectively) and little more than traces of expandable clay minerals (chiefly montmorillonite) and kaolinite (CINs of 2 and 6, respectively). The <0.5 μm fraction contains illite as the principal mineral (CIN of 40) with progressively lesser amounts of chlorite (CIN of 34) and expandable clay minerals (CIN of 26).

Our clay-mineral analyses differ from those of Locat (1996) for marine sediments from 17 other sites in the St. Lawrence Basin (Table 6) in that we find a smectite mineral (montmorillonite), as opposed to vermiculite, to be the dominant expandable clay mineral present. Smectite-group minerals are relatively easy to identify, but Moore & Reynolds (1997, p. 159) referred to vermiculite as the "Bad Boy" of clay minerals and stated, "It is difficult to identify positively because of its variable characteristics". We follow the recommendation of Moore & Reynolds (1997, p. 161) and use the term "expandables" when dealing with smectite-group minerals and vermiculite in soils, and we note which clay mineral dominates the expandable component. We also agree with the statement of Hughes *et al.* (1994, p. 37) "....we have thought that ion-exchange and similar treatments are often necessary second steps, but these treatments often 'create' clay minerals that do not match natural ones". We refrained from treating our samples with cations such as K or Mg in order to avoid creating a clay mineral not present in the natural sample. When one compares the data in Wilson's (1987) Tables 2.5 through 2.10, one sees just how easily a smectite can be confused with vermiculite after treatment with various cations. We nonetheless have full confidence in the relative proportions of tectosilicates to phyllosilicates reported by Locat (1996).

TABLE 6. PHYLLOSILICATE CONTENTS (%) OF MARINE SEDIMENTS AT SITES IN THE ST. LAWRENCE BASIN[1]

Site	Clay	Illite	Vrm	Chl	Phyl
		Champlain Sea Basin			
Gatineau	75	8	9	9	26
Buckingham	50	8	4	11	23
Plaisance	79	10	6	13	29
Lachute	76	9	5	14	28
St-Zotique	82	10	7	15	32
Varennes	83	9	7	13	29
Joliette	48	9	3	4	16
Yamaska	42	5	6	6	17
Louiseville	80	5	5	16	26
St-Léon	72	4	5	11	20
Batiscan	78	8	5	9	22
St-Alban	78	8	7	12	27
St-Etienne	28	2	2	5	9
		Goldthwait Basin			
St-Valliers	52	10	3	5	18
Cap-Chat	32	2	2	20	24
Sept-Iles	77	13	8	12	33
		Laflamme Basin			
Jonquière	45	2	2	11	15

[1] Compilation taken from Locat (1996). Sites in each basin are arranged from the most inland to the most seaward. Symbols: Vrm vermiculite, Chl chlorite, Phyl phyllosilicates.

TABLE 7. PROPORTION OF Fe AND Al OXIDES (wt.%) EXTRACTED FROM SELECTED SIZE-FRACTIONS OF THE ST-BARNABÉ AND HENRYVILLE CORE-SAMPLES

St-Barnabé						Henryville					
Depth m	Size µm	Citrate-dithionite		Ammonium oxalate		Depth m	Size µm	Citrate-dithionite		Ammonium oxalate	
		Fe	Al	Fe	Al			Fe	Al	Fe	Al
1	4–2	1.14	0.19	0.34	0.26	1	4–2	1.07	0.28	0.29	0.26
	2–0.5	0.78	0.28	0.51	0.39		2–0.5	1.72	0.28	0.34	0.43
	<0.5	1.43	0.38	0.69	0.68		<0.5	1.93	0.47	0.46	0.83
3	4–2	0.64	0.09	0.92	0.45	3	4–2	0.93	0.19	0.80	0.28
	2–0.5	1.07	0.28	1.54	0.68		2–0.5	0.86	0.19	0.69	0.45
	<0.5	2.43	0.66	2.86	1.89		<0.5	2.07	0.47	1.89	1.06
6	4–2	0.72	0.19	-	-	5	4–2	0.79	0.09	0.63	0.21
	2–0.5	1.29	0.28	1.43	0.60		2–0.5	1.36	0.19	1.03	0.38
	<0.5	1.36	0.57	2.86	2.12		<0.5	2.29	0.38	1.60	0.98
9	4–2	1.22	0.19	1.32	0.60	7	4–2	0.50	0.09	0.46	0.14
	2–0.5	1.00	0.38	2.46	0.98		2–0.5	0.86	0.19	1.20	0.45
	<0.5	2.28	0.76	2.83	2.12		<0.5	1.64	0.47	2.46	1.28
11	4–2	0.50	0.19	1.03	0.38						
	2–0.5	0.43	0.28	1.32	0.68						
	<0.5	2.57	0.76	3.20	2.12						

Oxide minerals

The weight percent of iron and aluminum oxides, expressed as Fe_2O_3 and Al_2O_3, extracted by the DC and AAO procedures from size fractions that were <4 µm, are presented in Table 7, with the Fe_2O_3 results plotted in Figures 4a, b. With minor exceptions for iron oxide, the extractable Fe and Al oxides increase as the particle size decreases.

Interpretation of the results of selective dissolution procedures is not completely straightforward. Treatment with DC is known to dissolve hematite, goethite and ferrihydrite, but DC is not a good solvent for magnetite. AAO is known to dissolve magnetite and ferrihydrite, but is not a good solvent for hematite or goethite (Sheldrick 1984). It is not certain how completely the limitations of DC and AAO apply to magnetite, hematite and goethite at the very small particle-sizes present in these samples (Torrance 1990), but Mössbauer spectroscopy of sediment from St-Léon (near St-Barnabé) demonstrated that DC was able to deplete magnetite to below the detection limit (Torrance *et al.* 1986). Both DC and AAO are aggressive against layer silicates (Borggaard 1988), with AAO, because of its acidity, being the more aggressive. This almost certainly contributes to the high rates of extraction from the <0.5 µm fraction in these samples, especially of aluminum oxides by AAO. This problem and the consistently smaller amounts of aluminum oxides extracted relative to iron oxides extracted suggest that aluminum oxides are unlikely to be of significance to the geotechnical behavior. Regardless of these problems with the selective dissolution procedures, the relative amounts of iron oxide extracted by DC and AAO suggest that magnetite is an important component of the iron oxide minerals below 3 m at St-Barnabé and in the 7 m sample at Henryville. The ratio of magnetite to other iron oxides is higher at St-Barnabé.

The presence of magnetite (partially oxidized to hematite) has been confirmed by Mössbauer spectroscopy in samples from 4 m in the Henryville core and from 9.7 m in the St-Barnabé core (L.H. Bowen, pers. commun., 1992). Magnetite was not detected at 1 m depth at St-Barnabé (probably because of destruction by weathering). The lesser amount of Fe extracted by AAO than by DC at 1 m at St-Barnabé also suggests oxidative destruction of any magnetite originally present.

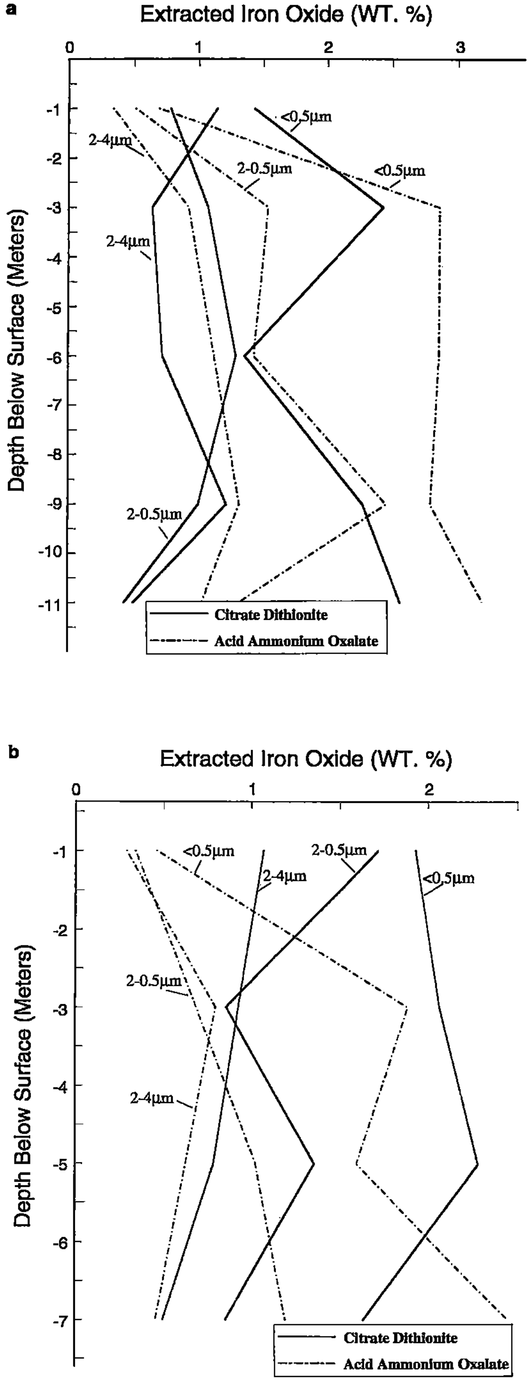

FIG. 4. Variations with depth in wt.% iron oxides extracted from selected size-fractions a) at St-Barnabé and b) at Henryville.

GEOTECHNICAL SIGNIFICANCE

The current mineralogical investigation represents the first report of the mineralogy of Champlain Sea sediments in which the silt and clay fractions have both been separated, in which the clay-sized fraction has been divided into 2–0.5 µm and <0.5 µm subsets, and in which the iron oxides have been investigated by a combination of Mössbauer spectroscopy and only moderately aggressive agents of chemical extraction. The very great overestimations of the quantities of iron and aluminum oxides arising from use of a procedure involving very aggressive extraction (multiple alternations of strong acid and strong base) on the Champlain Sea sediments, which most previous investigators have adopted, was discussed by Torrance (1995).

As indicated in the introduction, the main geotechnical problems with the Champlain Sea sediments derive from the high sensitivities and quick-clay behavior that these marine sediments may exhibit after the pore water salinity has been reduced to low values (<2‰, as has occurred at these sites). Tomas (1987) performed a range of geotechnical tests on the same cores as investigated herein; pertinent results are included, along with selected results from these mineralogical investigations, in Table 8, in order to allow assessment of how mineralogical differences may explain some of the behavioral differences. Caution must be exercised in this process because of the range of other factors that may be involved (Torrance 1983), and the fact that the relatively small number of samples analyzed do not exhibit the full range of properties and behavior exhibited by the Champlain clays.

Both the Henryville and the St-Barnabé cores exhibit their highest remolded strength and liquid limit and their lowest sensitivity at the 1 m depth. Whereas the remolded strength and sensitivity measurements are partially explained on the basis of the lower water content near the surface, the increase in liquid limit is best explained by the decreased pH, the higher proportion of exchangeable Ca and Mg, the production of expanding clay minerals as weathering proceeded, and by the oxidizing conditions (Tomas 1987) at this depth. The 1-m-depth samples are definitely located within the zone of pedological weathering.

The geotechnical properties at the two sites are substantially different below 1 m. Remoulded shear-strength, water content and liquid limit are higher at Henryville, whereas the liquidity index and sensitivity are lower. Extractable oxide contents are approximately the same in the two cores and do not appear to account for the differences. The greater amount of clay-sized particles, the smaller proportion of tectosilicates, and the tendency for more expanding clay minerals at Henryville, considered together, would be expected to result in the liquid limit being higher, which in turn would lead to a higher content of water in the sediment for comparable overburden conditions.

TABLE 8. SUMMARY OF KEY DATA FOR THE ST-BARNABÉ AND HENRYVILLE CORES

Depth (m)	1	2	3	4	5	6	7	8	9
				St-Barnabé core					
1	47.5	59	19	1.43	16.3	53.7	19.7	47.3	3.8
3	39.0	64	5.6	1.87	1.3	35.3	17.2	54.9	24.6
6	40.1	82	17.7	1.54	1.3	35.3	17.7	45.0	17.7
9	34.8	76	9.6	2.00	1.7	37.0	17.3	45.6	27.1
11	37.2	64	7.8	1.60	0.7	30.0	16.5	41.0	53.4
				Henryville core					
1	45.0	52	55.4	2.06	110.0	81.0	29.0	35.5	1.4
3	50.0	65	13.4	1.67	2.4	57.2	25.2	60.5	9.6
5	56.0	47	13.0	1.66	1.7	61.8	25.9	61.3	9.1
7	33.8	64	19.6	1.09	1.9	46.0	20.3	46.6	4.6

Column headings: 1: wt.% <2 μm fraction, 2: wt.% tectosilicates, 3: REIC, <16 μm fraction, 4: wt.% oxides, 5: Remolded strength (kPa), 6: Liquid limit, 7: Plastic limit, 8: Moisture content, 9: Sensitivity.

Depth (m)	pH	Salinity	Pore-water cations				CEC	Exchangeable cations			
			Na	K	Ca	Mg		Na	K	Ca	Mg
					St-Barnabé core						
1	6.5	-	-	-	-	-	34.1	1.4	1.0	11.5	12.4
3	8.4	0.81	430	30	16	18	27.0	3.2	1.3	11.9	6.1
6	8.5	0.90	570	38	26	10	20.7	4.9	1.6	13.2	5.4
9	-	0.81	470	31	23	7	23.0	4.1	1.5	10.2	4.5
11	9.1	0.78	360	24	20	6	19.1	3.9	1.3	5.5	3.3
					Henryville core						
1	7.1	-	-	-	-	-	41.9	0.9	0.2	19.3	15.5
3	7.7	0.5	90	10	107	50	12.3	0.6	0.9	13.8	6.3
5	8.1	0.4	110	15	31	45	23.5	0.7	1.0	20.9	8.2
7	8.6	0.5	130	16	25	24	18.6	0.4	0.6	17.6	4.7

Salinity is expressed in g/L, and the concentration of pore-water cations, in mg/L. Both the cation-exchange capacity (CEC) and the concentration of exchangeable cations are expressed in meq/100 g.

Below the weathering crust, the Henryville and St-Barnabé cores are not similar. Sensitivity ranges between 4 and 10 at Henryville, but is greater than 17 at St-Barnabé, where it generally increases with depth, over the depth investigated. The remolded strength is low for both cores, below the one meter depth, but generally slightly higher at Henryville. Quick clay (sensitivity >30, remolded strength <0.5 kPa) is not present at Henryville, but will be present at slightly greater depth at St-Barnabé, if the remolded strength trend continues with depth. Its probable presence is suggested by nearby large flowslide scars (Karrow 1972).

We will not succumb to the temptation to search for all the possible correlations among the geotechnical properties at each site and the chemical and mineralogical parameters, with the hope of attributing a cause to each relationship. The total number of samples analyzed and the number of factors that can influence behavior make such an approach very risky, particularly where correlations are weak. Rather, we will attempt to throw light on the importance of the two factors investigated in considerable detail that were found to be problematic in previous investigations, namely the role of expanding clays and the role of oxide minerals.

The role of expanding clays will be elucidated through use of the "Relative Importance of Expandable Clay" index (RIEC) for each sample. The RIEC is derived by multiplying the percentage of each size-fraction <16 μm in the sample by the CIN for the expandable clay in that fraction and adding the products for all the <16 μm size-fractions. These values are tabulated in Table 8. (Note that the RIEC does not give the % expandable clay in the samples, but rather it indicates the relative amounts.) If the RIEC values for both sites are plotted *versus* the sensitivity (Fig. 5), the data

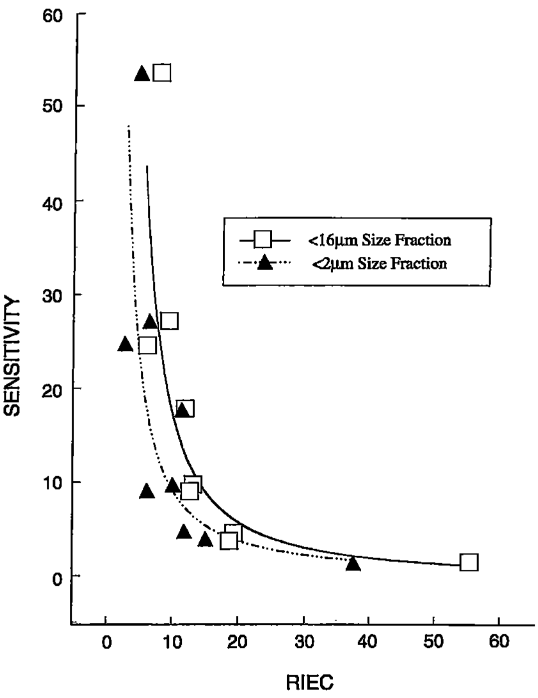

FIG. 5. Sensitivity *versus* RIEC (Relative Importance of Expandable Clay) index for <16 μm and <2 μm size fractions.

represent a continuum and exhibit a strong relationship whereby the sensitivity decreases as the RIEC increases. Similar calculations for the total proportion of nonswelling clays would show the reverse relationship. One of the reviewers has suggested that the remoulded shear strengths for lower-sensitivity samples are too high (as a consequence of too little remoulding). This is a possibility that is now impossible to check, but if the liquidity index is calculated and plotted *versus* the RIEC, the trend remains, although not quite as strongly expressed. These RIEC relationships support the assertions by Quigley (1980) and Torrance (1983) that the presence of increasing quantities of expandable clays in the marine clays works against the development of high sensitivities.

The question arises as to whether the expandable clays were present at the time of sediment accumulation or have been derived by post-depositional weathering. It seems probable that both scenarios are involved. The higher RIEC values for the sample closest to the top of core at each site is suggestive that at least some of the expandable material in these samples is derived by weathering since deposition. The relatively consistent RIEC values at each site below the oxidized near-surface zone are suggestive that some of the expandable material was present at the time of deposition. The higher RIECs at Henryville are consistent with contributions of Appalachian sources to the sediment, as opposed to the Canadian Shield origin at St-Barnabé. The Appalachian highlands were covered by ice for a shorter period of time, during the Pleistocene, than was the Canadian Shield, allowing for the generation of more expandable soil clays. In addition, the rock types in the Applachian highlands are more susceptible to weathering and production of expandable clays in the soil than those in the Canadian Shield.

The quantities of citrate–dithionite-extractable iron and aluminum oxides do not differ greatly among samples, and, in this limited number of samples, do not show any strong relationship to any of the geotechnical parameters. We suspect that the aluminum extracted derives principally from attack of the layer silicates by the extracting agents, with the more acidic AAO extractant, not surprisingly, being the more aggressive. The main source of the iron (confirmed by the Mössbauer results) is from iron oxides produced by weathering or present in the sediment since the time of sedimentation. Given the improbability of conditions for the weathering of other iron-bearing minerals and for the synthesis of magnetite occurring throughout the sediments, the magnetite is almost certainly inherited from magnetite that is present as an accessory mineral in both source areas and has been present since sedimentation. Depositional origin is also probably the case for most of the hematite and goethite (most probably hematite is dominant) below the weathering crust, because Tomas (1987) found strongly reducing conditions below 2 m at St-Barnabé and below 2.5 m at Henryville, conditions under which hematite or goethite should not form. The amounts of both aluminum and iron extracted from the sediment, with few exceptions, increase as the particle size decreases. The relative amounts of aluminum from the different size-fractions seem reasonable for a time-dependent process of extraction. The iron extraction by citrate–dithionite is dependent on the amount of reducing agent (Na dithionite) added (adequate for more than the amount of iron oxides present in this instance), and the procedure is designed to allow sufficient time for essentially the full effect to be realized.

The very small particles of iron oxide present in these sediments are considered to be associated with the surfaces of particles of the other minerals in the system (Løken 1970, Yong & Ohtsubo 1987). Assuming this to be the case, the trend to greater extraction of iron oxide from the finer fractions is expected, but the relative amounts extracted indicate somewhat less iron oxide per unit surface area in the finer fractions. Calculations based on reasonable assumptions for the size of the oxide particles, as in Torrance (1990), indicate that only a small fraction of the particle surfaces in any of the size fractions are coated by oxides. Neutralization (by oxide coatings) of a minority of the negative surface-charges of the mineral grains should not be a major effect on geotechnical behavior. The iron oxides more probably serve as a cementing agent that increases the undisturbed strength of these sediments, beyond that expected from the effective stresses they have experienced, by being strategically located around points of particle contact and acting by a means analogous to "spot welding" of metals.

CONCLUSIONS

The principal conclusions from this investigation, some new and some agreeing with those of previous research by others, are summarized below. 1) The sediments in the St-Barnabé and Henryville core samples were confirmed to be neither predominantly clay-size in texture nor predominantly clay mineral in composition. 2) The suite of phyllosilicates present consists dominantly of illite and chlorite, with some smectite (most abundant where pedological weathering has occurred). 3) The relative proportions of the various tectosilicates and of the various phyllosilicates can change substantially within a small range in depth, such that a single sample does not necessarily yield a reliable quantification of the relative abundances of minerals in the sediments at a specific location. 4) Inverse relationships between expandable clays and sensitivity, and between expandable clays and liquidity index, support previous assertions that expandable clays work against the development of high sensitivities. 5) Provenance appears to play an important role in controlling the abundance of expandable clay minerals below the zone of weathering at the sites investigated, and in controlling the relative abundances among the tectosilicates. 6) Although a modest positive correlation exists between iron oxide contents and undisturbed strength of the sediments in these cores, the minimal amounts of iron oxide present suggest that the effect is related to cementation at points of contact of constituent mineral grains.

ACKNOWLEDGEMENTS

Many people and organizations made possible the collection and analyses of samples. The Québec Division des Sols et Chaussées provided the samples, separation procedures were done in the Geotechnical Science Laboratories, Department of Geography, Carleton University, X-ray diffraction was done at the Department of Earth Sciences, Carleton University and at San Diego State University. Ron Conlon, Ann Brereton and Nina Tomas assisted with sample characterization. We are indebted to Dr. L.H. Bowen, North Carolina State University, Raleigh, N.C. for carrying out the Mössbauer spectroscopic analyses. R.W. Berry conducted the mineralogical investigation while on sabbatical leave. Dr. J. Locat and Cand. Real T. Løken are thanked for helpful comments.

REFERENCES

BERRY, R.W. (1987): Mineralogical and particle size analysis of Leda clay samples: analytical techniques. *Carleton Univ. Geotechnical Science Laboratories, Laboratory Technique Rep. Ser., Rep.* **13**.

BORGGAARD, O.K. (1988): Phase identification by selective dissolution techniques. *In* Iron in Soils and Clay Minerals (J.W. Stucki, B.A. Goodman & U. Schwertmann, eds.). *NATO Adv. Study Inst. Ser.* **C 217**, 83-98. Reidel, Dordrecht, The Netherlands.

GADD, N.R. (1962): Surficial geology of Ottawa map area, Ontario and Quebec. *Geol. Surv. Can., Pap.* **62-16**.

________ (1986): Lithofacies of Leda clay in the Ottawa Basin of the Champlain Sea. *Geol. Surv. Can., Pap.* **85-21**.

HUGHES, R.E., MOORE, D.M. & GLASS, H.D. (1994): Qualitative and quantitative analysis of clay minerals in soils. *In* Quantitative Methods in Soil Mineralogy (J.E. Amonette & L.W. Zelazny, eds.). *Soil Sci. Soc. Am., Misc. Publ.*, 330-359.

KARROW, P.F. (1972): Earthflows in the Grondines and Trois Rivières areas, Quebec. *Can. J. Earth Sci.* **9**, 561-573.

LOCAT, J. (1996): On the development of microstructure in collapsible soils. *In* Genesis and Properties of Collapsible Soils: Proceedings of the NATO Advanced Research Workshop on Genesis and Properties of Collapsible Soils (Loughborough, U.K., 1994) (E. Derbyshire, T. Dijkstra & I.J. Smalley, eds.). Kluwer, Dordrecht, The Netherlands (93-128).

________, LEFEBVRE, G. & BALLIVY, G. (1984): Mineralogy, chemistry, and physical properties interrelationships of some sensitive clays from eastern Canada. *Can. Geotech. J.* **21**, 530-540.

LØKEN, T. (1970): Recent research at the Norwegian Geotechnical Institute concerning the influence of chemical additions to quick clay. *Geol. Fören. Stockholm Förh.* **92**(2), 133-147.

MOORE, D.M. & REYNOLDS, R.C. (1997): *X-Ray Diffraction and the Identification and Analysis of Clay Minerals* (2nd ed.). Oxford University Press, New York, N.Y.

QUIGLEY, R.M. (1980): Geology, mineralogy and geochemistry of Canadian soft soils: a geotechnical perspective. *Can. Geotech. J.* **17**, 261-285.

SHELDRICK, B.H., ed. (1984): *Analytical Methods Manual 1984.* Land Resource Res. Inst., Agriculture Canada, Ottawa, Contrib. **8430**.

TOMAS, N. (1987): *Characterization of Two Champlain Sea Sediments: St. Barnabé and Henryville, Quebec.* B.Sc, thesis, Carleton Univ., Ottawa, Ontario.

TORRANCE, J.K. (1983): Towards a general model of quick clay development. *Sedimentology* **30**, 547-555.

________ (1988): Mineralogy, pore-water chemistry, and geotechnical behaviour of Champlain Sea and related sediments. *In* The Late Quaternary Development of the Champlain Sea Basin (N.R. Gadd, ed.). *Geol. Assoc. Can., Spec. Pap.* **35**, 259-275.

________ (1990): Oxide minerals in the sensitive post-glacial marine clays. *Applied Clay Sci.* **5**, 307- 323.

________ (1995): On the paucity of amorphous minerals in the sensitive post-glacial marine clays. *Can. Geotech. J.* **32**, 535-538.

________, HEDGES, S.W. & BOWEN, L.K. (1986): Mössbauer spectroscopic study of the iron mineralogy of post-glacial marine clays. *Clays Clay Minerals* **34**, 314-322.

WILSON, M.J. (1987): *A Handbook of Determinative Methods in Clay Mineralogy.* Blackie and Son Ltd., Glasgow, U.K.

YONG, R.N. & OHTSUBO, M. (1987): Interparticle action and rheology of kaolinite – amorphous iron hydroxide (ferrihydrite) complexes. *Appl. Clay Sci.* **2**, 63-81.

Received November 26, 1997, revised manuscript accepted December 12, 1998.