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Sediment dispersion: part 1, fine sediments and significance of the silt/clay ratio

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Abstract

The dispersion of fine sediment is greatly influenced by factors that induce flocculation, and which thereby determine whether particulates will settle in aggregate form or as discrete grains. The transport and deposition of silt and clay particulates in both marine and non-marine environments may be influenced by flocculation. Because the transport of sediment-associated contaminants is largely influenced by the behaviour of sub sand-size material, it is important to understand the factors which influence patterns of deposition. The silt/clay ratio has been used in an attempt to simplify description of the physical processes of sediment/water interaction, and most examples have been drawn from the Great Lakes. The silt/clay ratio has been related to other characteristics of the total particle-size distribution. As an indicator of many sedimentary conditions, it must be coupled with other measurements of particle-size.

Introduction

Dispersion is the spread of materials caused by their movement between a source point and an area of deposition; it is the net result of numerous interactions between confining factors such as bathymetry and size and shape of an aqueous environment, and forcing functions such as wave motion and currents, and the differential response by particulates of various size and suspended load concentrations. This contribution attempts to relate bottom sediment texture to dispersion by means of simple particle-size characteristics and to assess, to what extent, the sedimentary environment can be characterised by limited sediment textural information. It is intended to provide a 'bridge' between detailed process research and the more limited needs of survey and monitoring. The contribution is presented in two parts. In part 1, the emphasis is on fine sediments and the use of measurements, such as the silt/clay ratio, as a means of describing dispersion. Interpretations based on moment measure analyses have been used to aid understanding of this ratio. Data are drawn from three different sites in the Great Lakes (Kingston, Niagara & Tobermory; Sly, 1969) and are based on sub-samples of Shipeck bottom grab samples from 843 locations. Analytical procedures, surficial geology, textural and geochemical interpretations have been reported in (Sly, 1983[1], 1983[2], 1984; Sly & Sandilands, 1987).

For the purpose of this contribution, the phi scale ($-\log_2$ diam. mm) is applied to particle-size data, with the sand/silt boundary set at 4 phi (0.063 mm) and the silt/clay boundary at 8 phi

(0.004 mm). Some authors define the silt/clay boundary at 9 phi (0.002 mm); the difference is noted when present.

Use of moment measures

Textural analyses of sediments have been used to identify and differentiate between sedimentary environments (Visher, 1969; Middleton, 1976). In some low energy environments such as deep or restricted marine waters and lakes, where coarse particulates (sand/gravel) are absent, the silt/clay ratio has been used as an indicator of sedimentary conditions (Pelletier, 1973).

In a detailed examination of textural characteristics of nearly 2000 samples from marine and lacustrine environments, Sly *et al.* (1983) used sample mean size, standard deviation, and skewness/kurtosis relationships to define High and Low Energy sediment regimes. The regimes are separated in the sand size fraction (Sly, this volume). Sly *et al.* (1983) noted that mixtures of materials between sand and cobble end-members, and sand and clay end-members resulted in repeating patterns in relationships between particle-size and standard deviation. These formed near mirror-images in the High and Low Energy sediment regimes (Fig. 1). Maximum standard deviations occurred in the intermediate-member gravels and silts. The minimum standard deviation values of cobble, sand and clay materials indicated very effective sorting of these end members of particle-size populations.

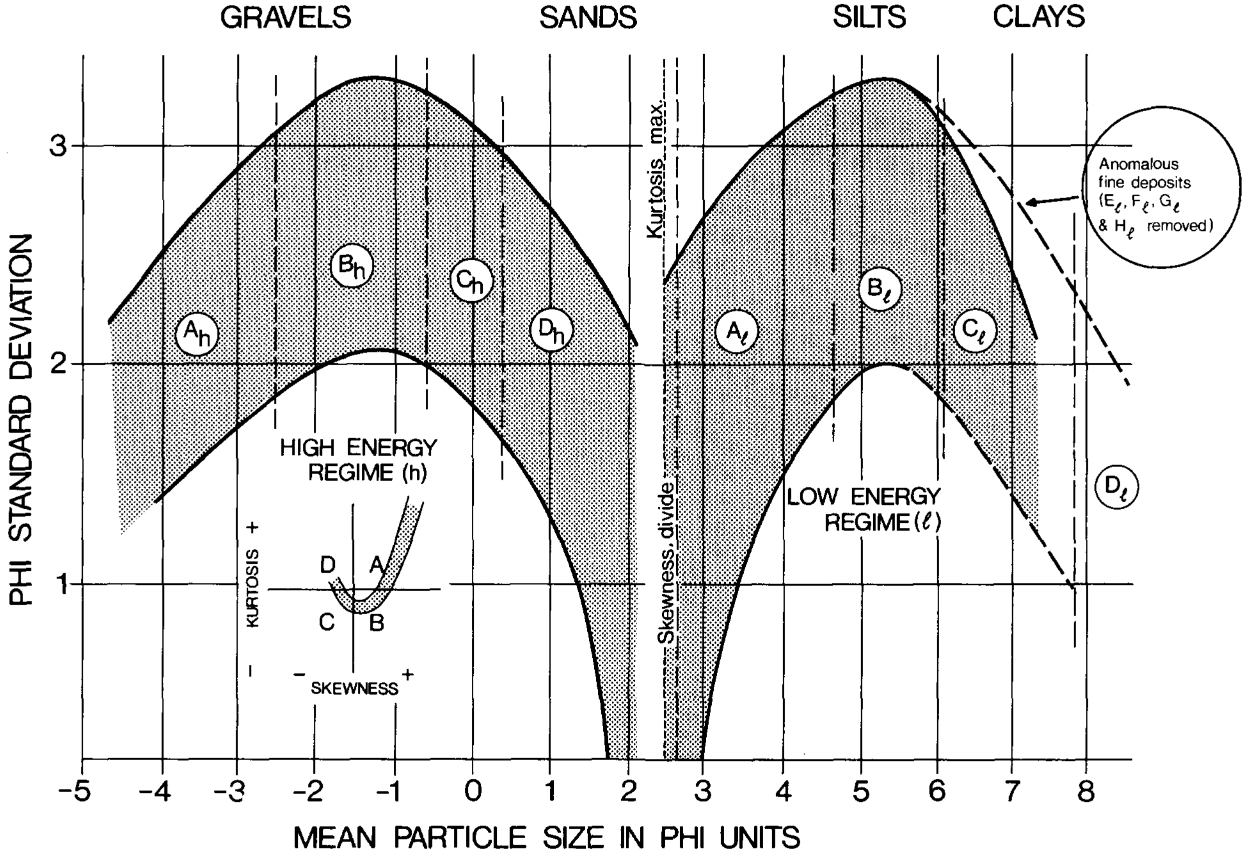


Fig. 1. Phi standard deviation in relation to phi mean particle-size, based on nearly 2000 samples. Skewness/kurtosis sectors A_h–D_h and A_l–D_l reflect decreasing hydraulic energy. Dashed line shows modified standard deviation envelope after removal of anomalous E_l–H_l sector samples, representing about 25 percent of the total number of samples.

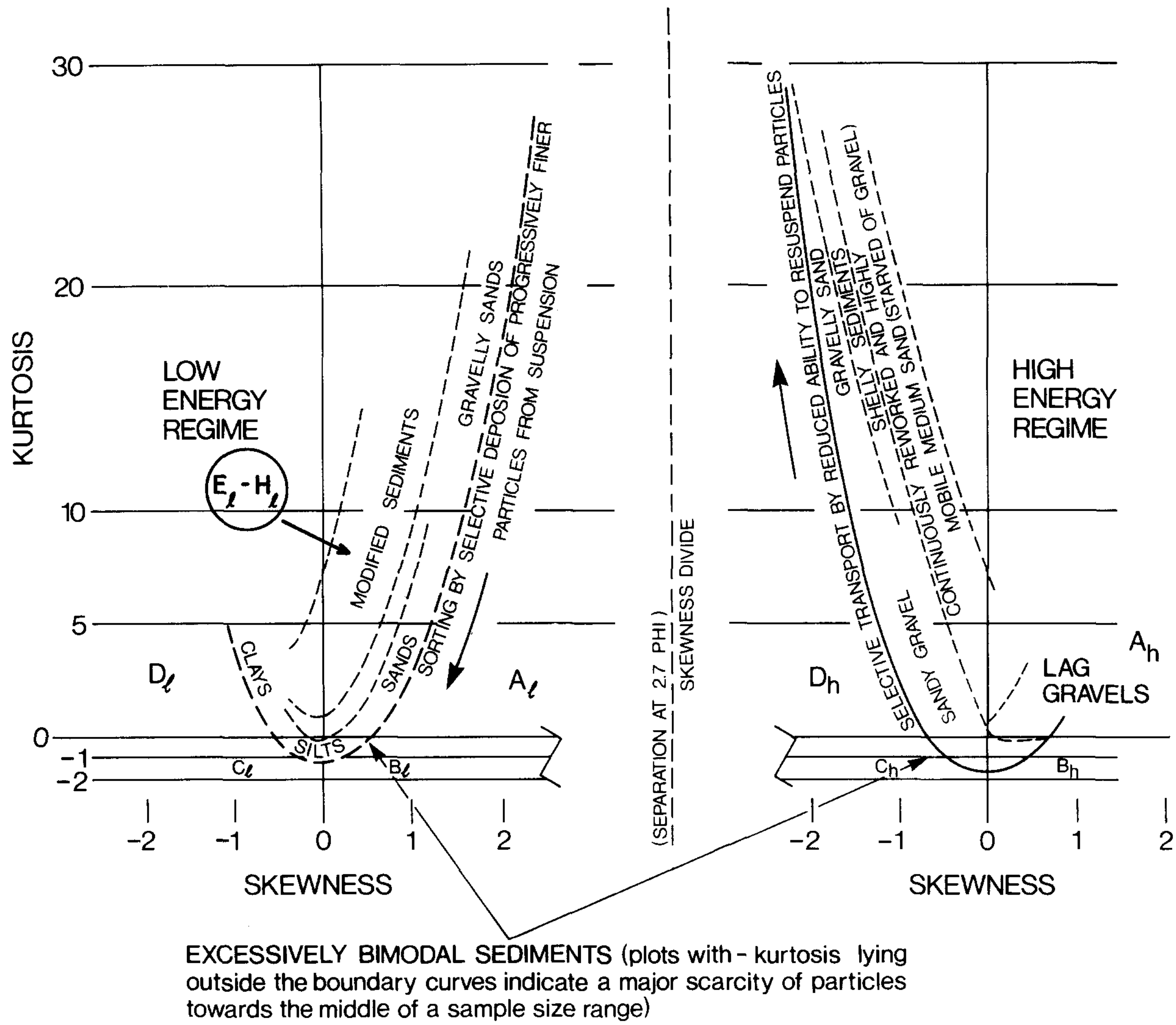


Fig. 2. Sediment types grouped according to skewness/kurtosis relationships. Samples near the outer boundary (limit) curve are generally closest to hydraulic equilibrium.

Skewness/kurtosis relationships were very sensitive to changes in the tails of particle-size distributions and were traced throughout the mean particle-size range between about − 5 to 8 phi. Depending upon the positive or negative signs of these values, four sectors were defined in each of the sediment energy regimes. In reducing hydraulic energy, these were defined as A_h–D_h (High Energy) and A_l–D_l (Low Energy), Fig. 2. Many textural distributions were recognised as anomalous, in that they departed significantly from an empirical depositional optimum. Four additional sectors (E_l–H_l), were used to characterise anomalous materials; they are generally comparable to sectors A_l–D_l, respectively (but contain some coarse particulates in otherwise fine sediments). The interpretations based on moment measures have been used to explain the significance of silt/clay ratios in selected Great Lakes bottom sediment data.

Silt/clay ratios

Based on particle-size settling characteristics, the amount of clay should generally increase, relative

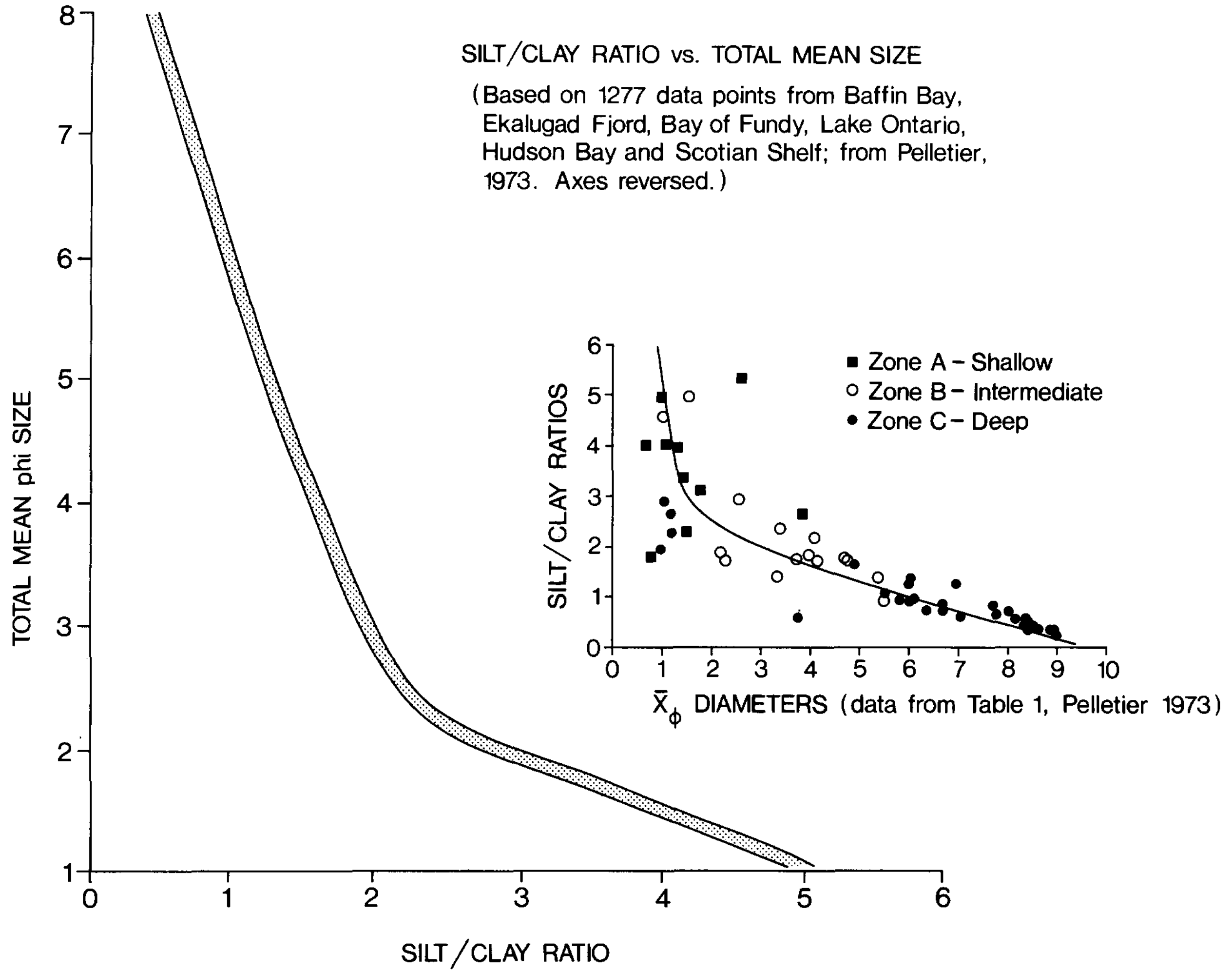


Fig. 3. Silt/clay ratio vs. total mean particle-size (modified after Pelletier, 1973). Zone A = 0–80 m depth; zone C > 500 m depth.

to silt, as the mean sample size becomes finer. This relationship seems to be characterised by the data presented in Fig. 3 (based on Pelletier, 1973). However an inflection occurs between High and Low Energy sediment regimes at about 2 phi. This implies that the relationships between the silt/clay ratio and mean sample particle-size are likely to be different above and below this point. The data show increasing deviation from the trend line at a mean size of about 4 phi and coarser. For comparison, the silt/clay ratios for Niagara sediments are shown in Fig. 4. Super-position of Pelletier's trend line over the Niagara data suggests that there is virtually no correlation between these two sets of data. Similar comparisons with Great Lakes data sets from Tobermory and Kingston have been equally unrewarding. Although Pelletier transformed his data (Σ silt + clay = 100%), and the Niagara, Tobermory and Kingston data are presented as original values, it was not expected that this would affect general comparison of sediments which contain only small amounts of coarser material. The reasons for an apparent lack of comparison between Pelletier's data and the Great Lakes' data provide a focus for subsequent discussion.

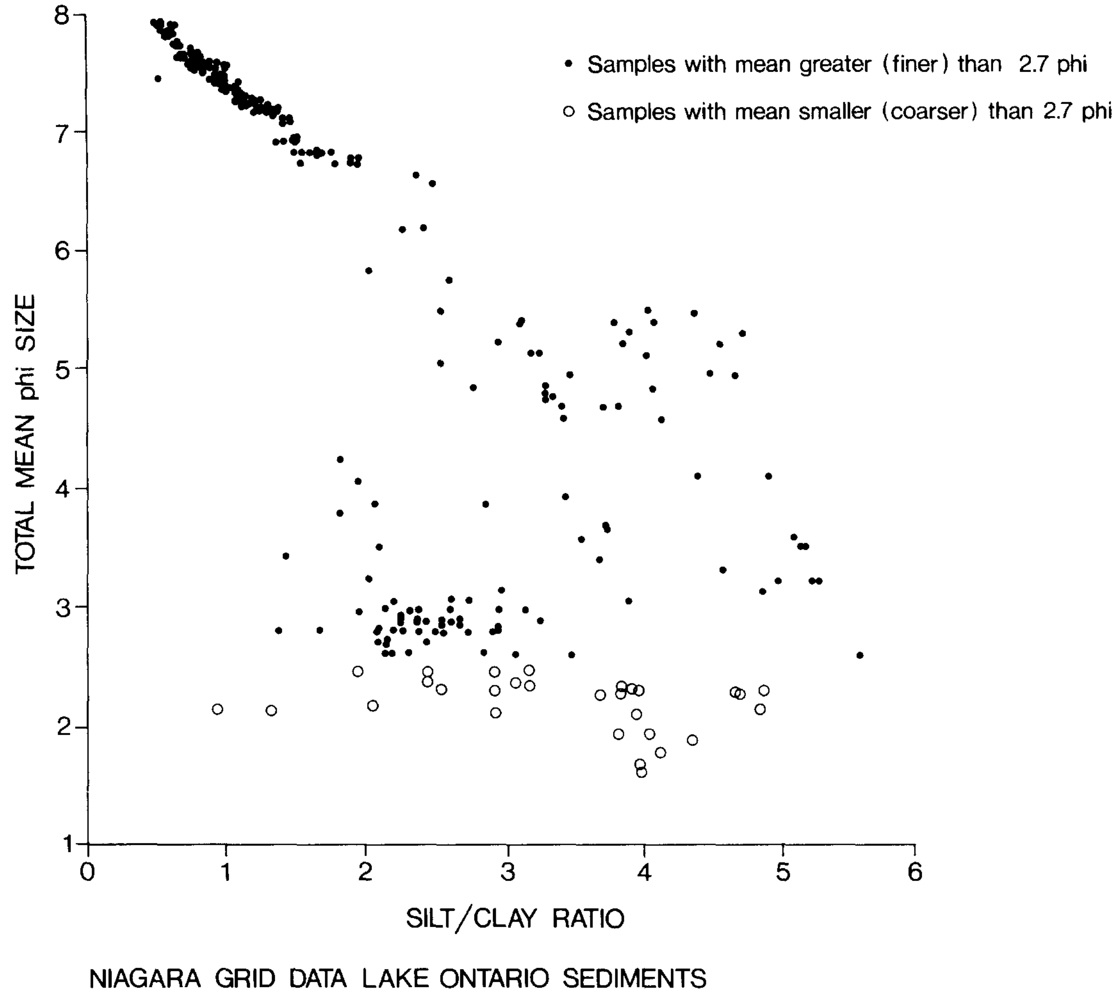


Fig. 4. Silt/clay ratio vs. total mean particle-size, Niagara sediment data.

Clay content

In Fig. 5, percent clay is plotted against total mean particle-size for each of three Great Lakes' sampling locations; trend lines, drawn through these data, are shown as curve overlays. The trends are similar but not identical. The Niagara data (N) show least deviation from their trend line. Parts of the Tobermory (T) and Kingston (K) data directly follow Niagara trends (t and k) and characterise sediments with a mean particle-size of 7 phi and finer. The greatest difference between the three data sets occurs in the range of 4–6 phi (sediments dominated by the silt size fraction).

Sample mean particle-size relationships

In Fig. 6, a trend line has been fitted through the Niagara data set linking sediment mean particle-size to the silt/clay ratio for samples conforming to decreasing hydraulic energies, empirically defined by skewness/kurtosis relationships (Sly *et al.*, 1983). Because sector D_1 material was not present at the Niagara study site, sector D_1 data from the Tobermory data set have been used to extend the relationships to a sediment mean particle-size of about 8.5 phi (coarse clay). The mean particle-size vs. silt/clay ratio for each skewness/kurtosis sector is plotted, together with com-

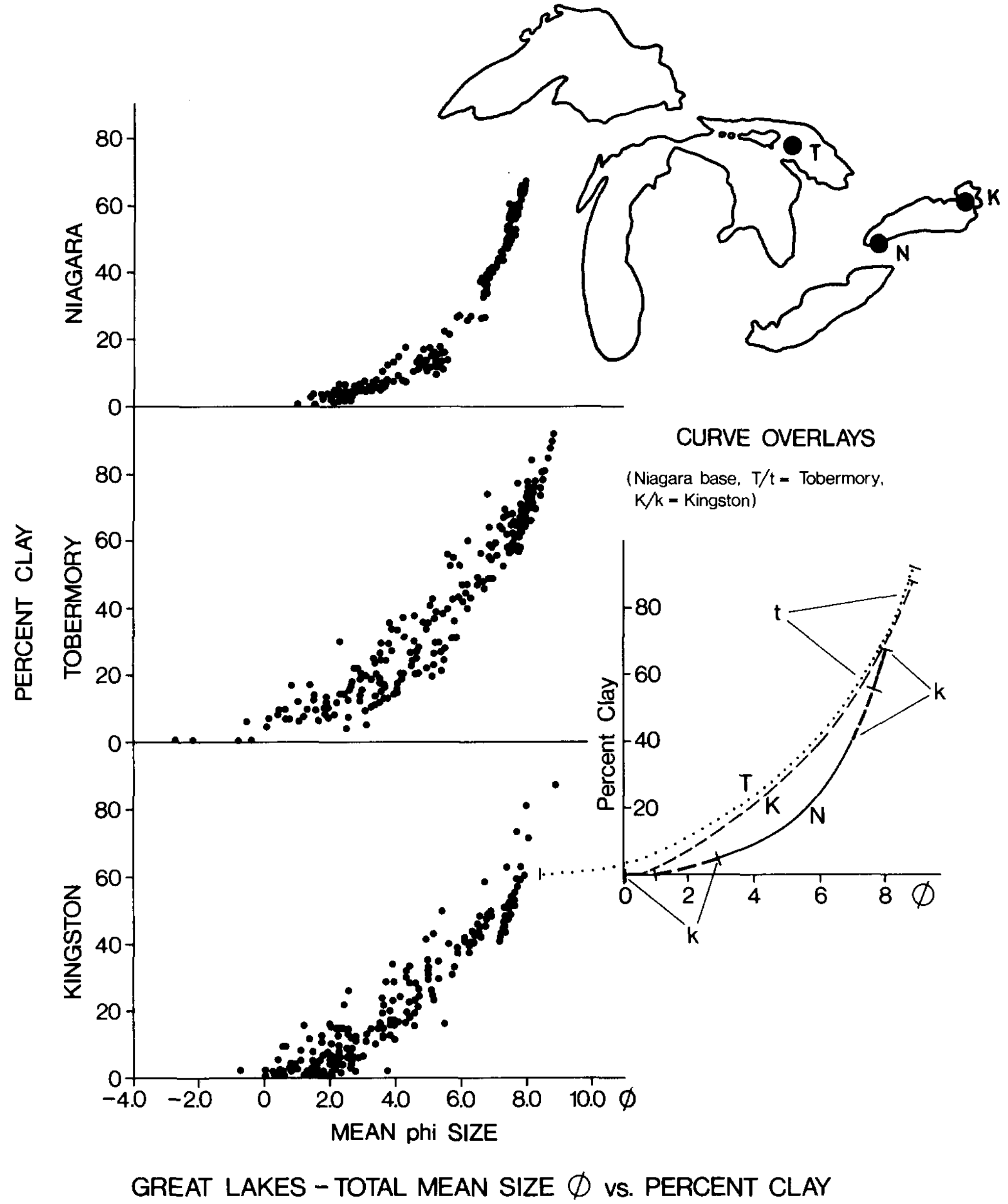


Fig. 5. Total mean particle-size vs. percent clay, from three Great Lakes areas: Kingston, Niagara and Tobermory. Depth ranges: K = 5–50 m, N = 5–100 m, T = 5–120 m.

parable plots of the anomalous sediment sectors E_l–G_l (H_l type materials are not present at the Niagara location). An interpretation of these data may be used to resolve apparent differences between the Great Lakes' data (Fig. 5) and those presented by Pelletier (1973), shown in Fig. 3.

In Table 1, the range of sample particle-size standard deviations that occur in each skewness/kurtosis sector are listed by sector for the Niagara, Tobermory and Kingston sampling locations. The mean particle-size for each sector (see also Fig. 6) is also listed. Standard deviations are smallest at the boundary between High and Low Energy sediment regimes (D_h–A_l) and the data also show that sector B_l–D_l sediments have lower standard deviations than sector F_l–H_l sedi-

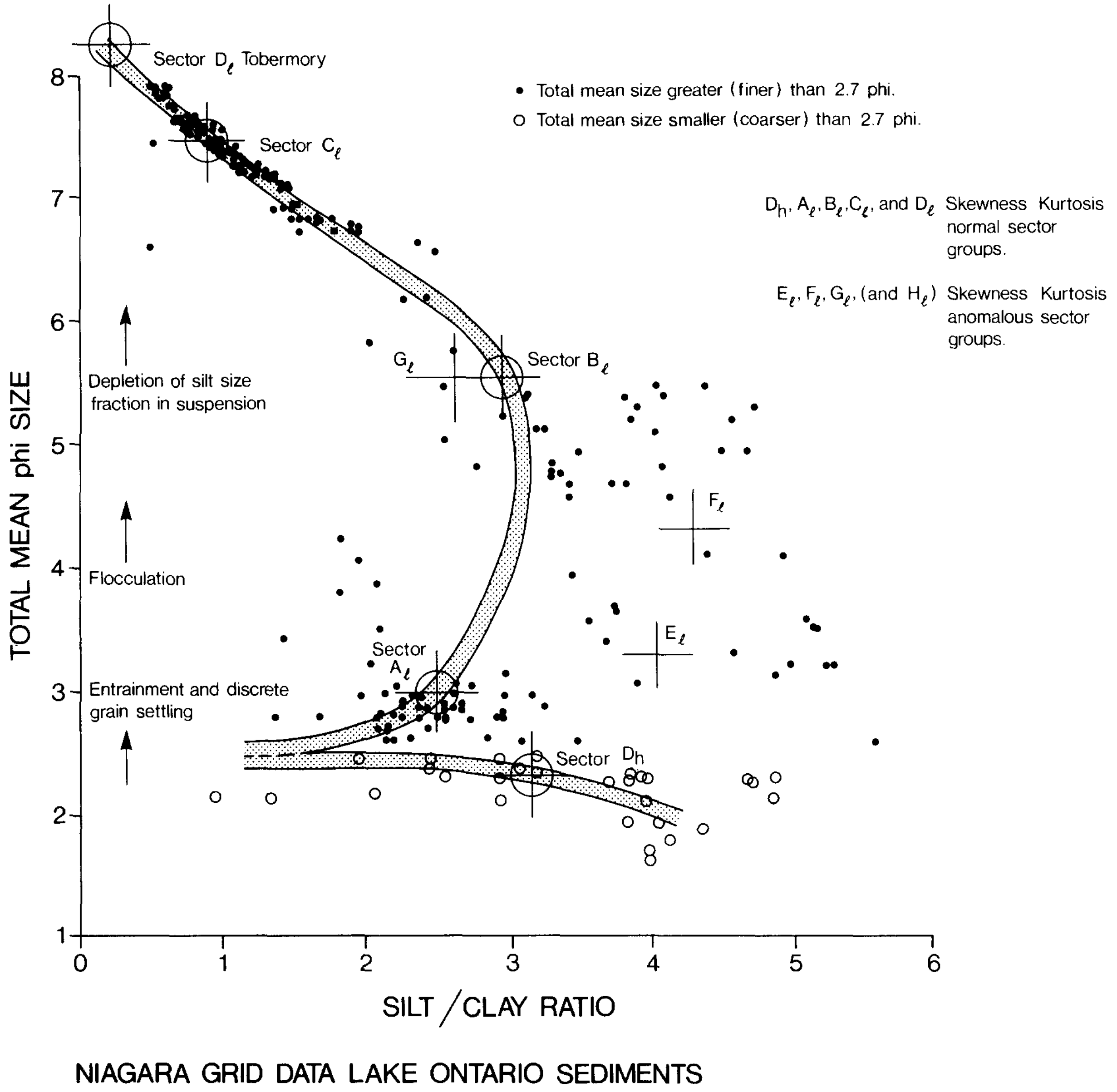


Fig. 6. Silt/clay ratio vs. total mean particle-size, with overlay of mean size value points for each skewness/kurtosis sector. Based on Niagara sediment data (D_h–C_l, and E_l–G_l), with additional Tobermory data provided to show position of sector D_l.

ments, of equivalent mean particle-size. Thus the mean is an inadequate expression, if used alone to characterise the texture of such samples.

In Fig. 7, the actual values of percent silt are plotted against percent clay, for all Niagara data. Since silt is related only to clay, in this figure, the effects of coarse fraction anomalies (sectors E_l–H_l) are excluded from the distribution plot. Separate notations of mean phi size refer only to sector D_h–D_l samples and these clarify the features of data presented in Fig. 6:

1) Open circle data, in Fig. 7, represent samples of High Energy regime sandy gravel (coarser than 2.7 phi), and their distribution trend generally overlaps that of finer sand (solid circles) from the Low Energy regime. Differentiation

Table 1. Mean values refer to the mean of all samples in each sector. Standard deviation is expressed by the upper and lower (range) values in each skewness/kurtosis sector.

Sector	Mean phi size and mean standard deviations									Regime
	Niagara			Tobermory			Kingston			
	n	Mean size	S.D.	n	Mean size	S.D.	n	Mean size	S.D.	
D_h	28	2.23	1.3–1.8	33	1.52	1.3–1.8	82	1.64	1.3–1.8	High Energy
A_l	47	3.06	1.3–1.8				4	3.65	1.3–1.8	Low Energy
B_l	48	5.55	2.0–2.5	6	5.25	2.0–2.5	13	5.81	2.0–2.5	(Normal
C_l	128	7.50	1.5–2.0	81	7.83	1.5–2.0	72	7.31	1.5–2.0	deposition)
D_l				35	8.34	1.5–2.0	2	8.43	1.5–2.0	
E_l	9	3.28	2.0–2.5	9	3.44	2.0–2.5	15	3.13	2.0–2.5	Low Energy
F_l	9	4.30	2.5–3.0	48	4.11	2.5–3.0	31	4.27	2.5–3.0	(Anomalous
G_l	2	5.51	2.5–3.0	42	5.91	2.5–3.0	22	5.55	2.5–3.0	deposition)
H_l				13	6.73	2.5–3.0	1	7.72	2.5–3.0	

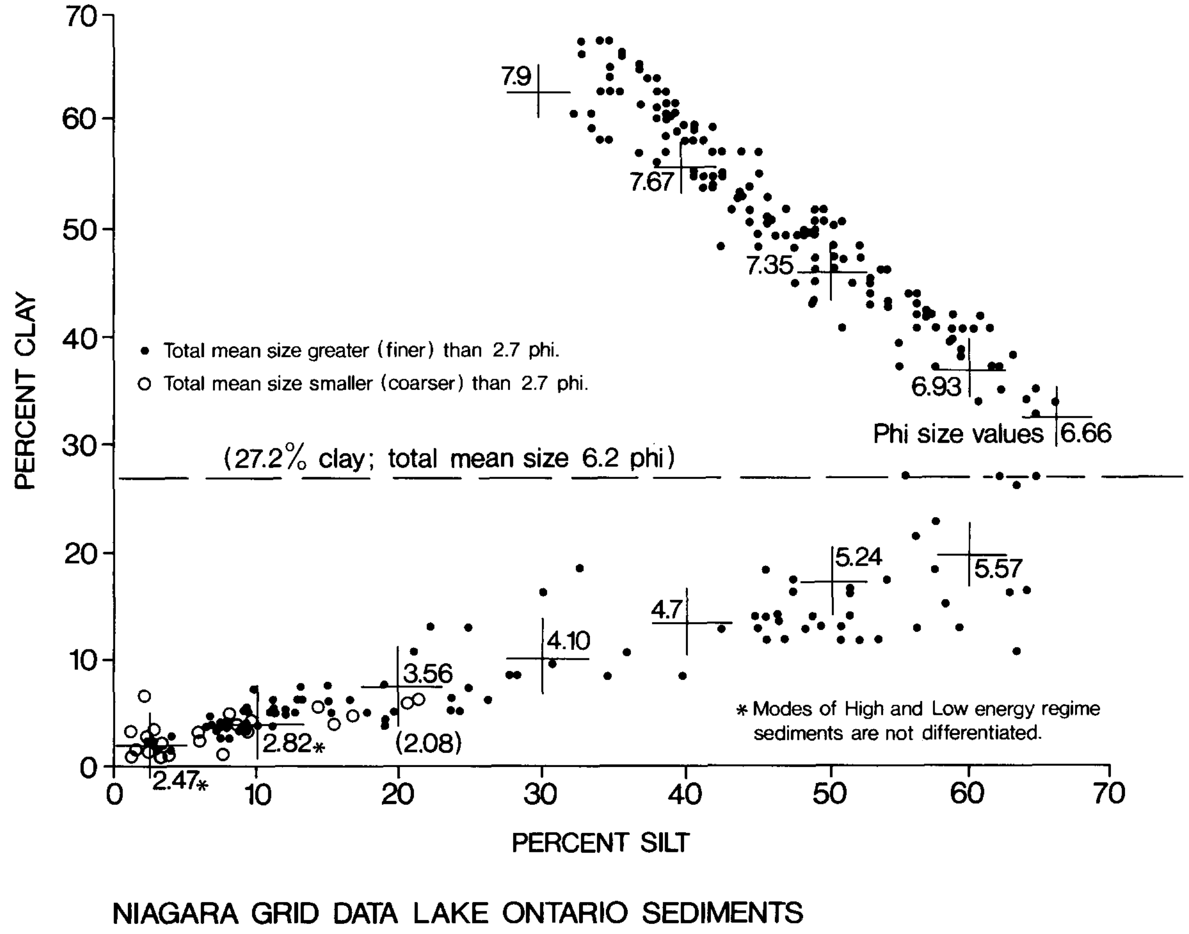


Fig. 7. Percent silt vs. percent clay in relation to mean particle-size, Niagara sediment data. The means of total sample particle-size given as notations, corresponding to 10% silt intervals, to show how the silt/clay ratio changes in relation to mean particle-size. * values refer to the mean particle-size of samples which lie close to the High and Low Energy regime boundary, ant that have not been differentiated; ( ) values refer to High Energy regime sediments; all other values refer to Low Energy regime sediments.

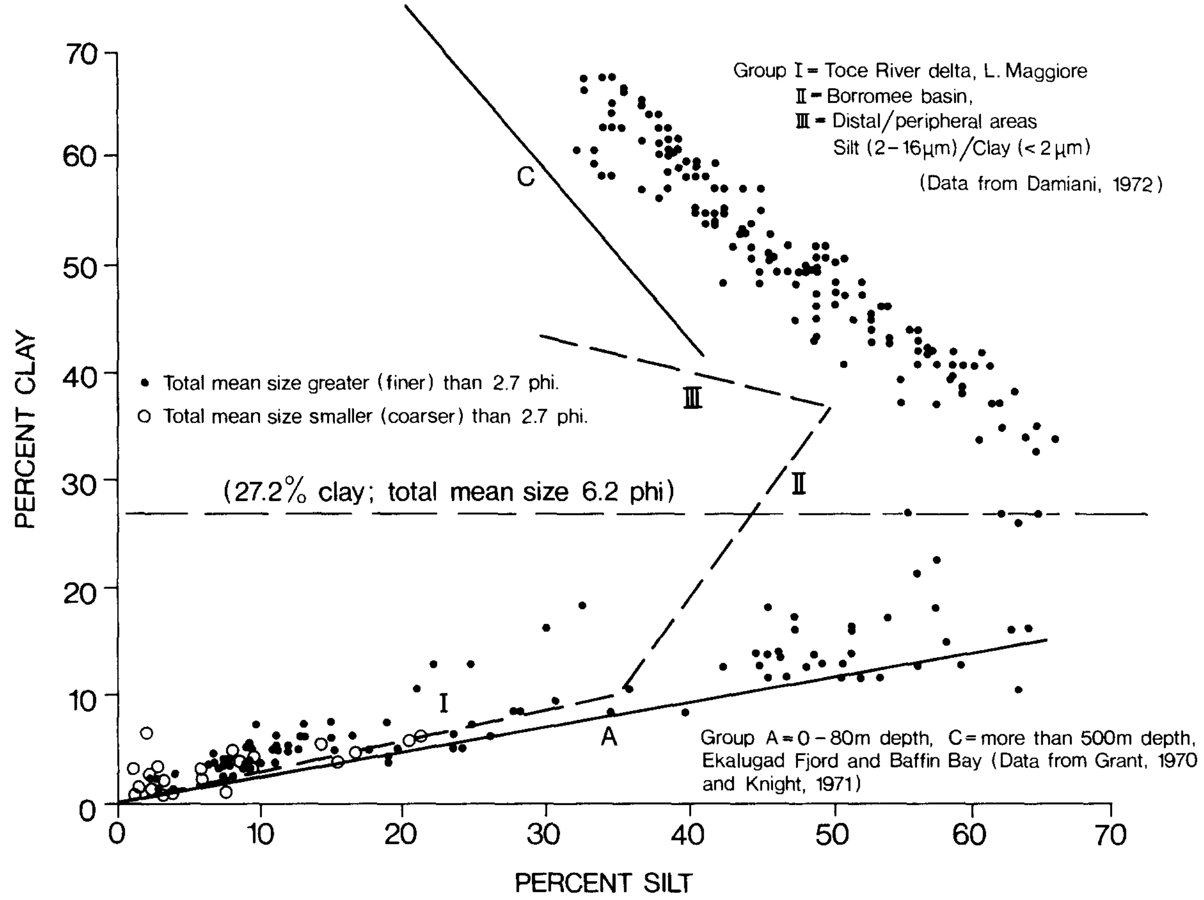
between the mean particle-sizes of these two regimes is not made at the 2.5 and 10% silt composition midpoints which represent all sample materials between 0–4.9 and 5.0–14.9% silt, respectively. However, at 20% silt the mean-particle size of Low Energy sediment is 3.56 phi, for the High Energy regime sediment it is 2.08 phi.

2) The steadily decreasing mean particle-size associated with the remaining silt/clay data points confirms not only the form of the distribution pattern but that, indeed, there is a clearly defined trend in the silt/clay ratio which is related to sample particle-size (a similar observation was made by Pelletier, 1973).

3) The silt content follows a near linear trend, increasing from about 1% silt content, in medium-coarse sands, to a maximum of about 65% silt. The peak occurs at an inflection point corresponding to a value of about 27% clay and a sediment mean particle-size of about 6.5 phi. At finer mean particle-sizes, the silt content again follows a near linear trend in which it decreases to about a 30% silt content at 8 phi; the corresponding value of clay content is about 70%.

4) There is remarkably little deviation from the trend of these data.

In Fig. 8, two additional sets of data trend lines have been superimposed. A plot of the percent silt (0.016–0.002 mm) vs. percent clay (< 0.002 mm) from the Toce River delta and Borromee basin of Lago Maggiore (Damiani, 1972) shows the same basic trends, although modified by the effects of



NIAGARA GRID DATA LAKE ONTARIO SEDIMENTS

Fig. 8. Percent silt vs. percent clay, Niagara sediment data with overlays of Lake Maggiore and marine sediment data (for explanation of overlay plots, see text).

a limited silt size fraction and a shift in the silt/clay boundary. Group A and C data (from Pelletier, 1973) are derived from a marine environment. The trend in the Group A data (shallow water) is remarkably similar to the comparable Niagara date set, and shares a common silt maximum. Group C data are generally similar to the Niagara data (those derived from deeper water) but exhibit a different slope and contain about 10% less silt for a comparable clay content. There is no evidence in any of these data to show that the silt/clay ratios in marine sediments are higher than in non-marine environments, as suggested by several authors (cited in Pelletier, 1973).

The data presented in Fig. 8 confirm consistent relationships between silt and clay, even though plots of the silt/clay ratio vs. sediment mean particle-size (Fig. 6) may lack clearly defined trends. The lack of comparison between Figs. 3 and 4 is due, mostly, to differences in resolution. Based on data from the Great Lakes, the total quantity of fines (silt + clay) varies significantly; from less than 10% in medium-coarse sands, to 12–15% in fine sands and to about 70% in silts.

Significance of fines

Based on Mississippi River data, Passega (1977) showed that deposition of fine materials from suspensions could be associated with bed samples when the mean particle-size of bed material was finer than about 2 phi (medium-coarse sand). The behaviours of suspended and bed load material do not appear to share this association under conditions of greater hydraulic energy that characterise materials coarser than 2 phi. Thus, the silt and clay fines in sector D_h material (Fig. 6) likely represent entrainment and entrapment of the suspended load, as suspensions mix with coarse material (or perhaps pass through the porous bed). The increasing silt/clay ratio associated with coarse bed material appears to be independent of bed material size; it may more nearly reflect the particle-size composition of the suspended load, rather than the deposition of some portion of it under conditions of reduced shear.

The increasing content of silt and clay fines in Low Energy deposits shows the effects of entrainment with fine sands, deposition as discrete particles, and flocculation (Fig. 6). The increase of silt/clay ratios in sector A sediments is caused by both entrainment and the settlement of coarse silts as discrete grains (Sherman, 1953). Kranck (1980), working with fresh and salt-water suspensions, noted that grain size distribution curves of flocculating materials showed little variation, although modal size decreased with increasingly finer sediments. Thus the more gradually changing silt/clay ratios in sediments of mean size between about 4 and 5.5 phi suggest that flocculation may be a particularly important depositional mechanism, depleting (nearshore at Niagara) suspensions of relatively constant amounts of silt and clay (though the size of the silt particles continues to decrease).

During the settlement of fines that form sediments whose mean particle-size is finer than about 5.5 phi, sedimentation occurs from suspensions in which the silt size fraction has been considerably depleted (Rosa, 1985). With respect to silt, there is a near linear increase in clay content in sediments finer than about 6.0 phi mean particle-size. The clay mineralogy of these sediments is essentially the same, illite being the dominant species (Thomas *et al.*, 1972, 1973). Modern sediments at all three Great Lake locations showed generally the same silt/clay ratios in relation to sediment mean-particle size, at values finer than about 7.0 phi. Conditions affecting slow deposition of modern deep-water sediments (Gibbs, 1985) throughout most of the Great Lakes are, therefore, essentially the same. This interpretation is further supported by Kranck (1980), who noted that, after some period of time, flocculated suspensions of similar sediment will have the same particle concentrations irrespective of initial concentrations.

Nepheloid layers near the bed in Lake Ontario (Sandilands & Mudroch, 1983) and other Great Lakes, are composed of very fine silt and clay particles. Since formation of these layers represents conditions under which flocculation has removed all but the finest grain sizes, their particle-size composition is likely to be very similar. The relatively slow settlement of remaining particles provides time to transport very fine sediment and to 'focus' it by entrainment in the circulation of deep mid-lake basins. Further, the apparent slow creep of contaminants across mid lake basins is likely a reflection of the effects of repeated partial depositions; these precede seasonal resuspension of the nepheloid layer which occurs during the fall overturn and winter isothermal period. To some extent, the same process also may occur when storm conditions erode fine sediments, marginal to deep water depositional basins, and re-mobilize fine particulates as a result of disaggregation.

Niagara sediments are much influenced by the source of materials from the Niagara River (Sly 1983[1] and 1983[2]). Modern rates of accumulation are high, amounting to about 2 mm/a^{-1} in D_h–A_l areas, 1.4–1.8 mm/a^{-1} in B_l areas and 0.1–0.5 mm/a^{-1} in C_l areas (Sly, 1983[1], 1983[2]). Therefore, the higher silt content for a given mean particle-size at Niagara, relative to either Tobermory or Kingston, can be explained on the basis of high concentrations in the suspended load. The differences in relationships between clay content and mean-particle size (Fig. 5) are to be expected, since flocs will incorporate larger individual grain sizes at progressively higher concentrations of suspended material (Kranck, 1980). As deposits become finer, further away from their source, a reversal in the silt/clay ratio should occur along the depositional/dispersal trajectory; Fig. 6 largely confirms this (see sediment distribution at Niagara; Sly, 1983[2]). The high standard deviation values of B_l sediments characterise poor sorting of silts/sands and silts/clays, typical of flocculent material. Local variations of exposure to wave action at the Kingston site allow entrapment of fines in otherwise coarse sediments at some sample locations; thus, some of these coarse sediment data are also comparable to the Niagara data (Fig. 5). Low rates of deposition at Niagara, Tobermory and Kingston are similar at greatest depths, where the trends in silt/clay ratio and clay content of the sediments are closely comparable.

The presence of anomalous sector E_l–H_l sediments, particularly at Tobermory and Kingston, is largely related to relict deposits (formed at lower lake levels) which are only partly covered by modern fine sediment. Rates of sediment accumulation, therefore, may have an important masking effect on the interpretation of textural data and likely account for the wider dispersions of Kingston and Tobermory data points (Fig. 4), relative to Niagara data which characterise rapid modern deposition.

Despite such conditions, there can be little doubt that the principal cause of variation in the silt/clay ratio vs. mean-particle size data (at Niagara) is the quantity of silt derived from the Niagara River. Excessive deviation in these data reflects both flocculation of large quantities of silt and relatively rapid and large scale fluctuations in suspended load concentrations. These result from the shifting position of the river plume, after it enters Lake Ontario, and impart spatial and temporal differences to the depositional zone.

Conclusions

The Great Lakes data demonstrate that Silt/clay ratios are not unique to a specific sample mean particle-size. As an indicator of sedimentary conditions, they must be coupled with sample mean size or, at least, sand composition data. Pelletiers' data and those from the Great Lakes both show, at mean size finer than about 2 phi, that there is a direct relationship between silt/clay ratios and mean size. However, the silt/clay ratio does not decline consistently with mean particle-size. There appears to be no relationship between the silt/clay ratio and the particle-size distribution of bottom sediments, where bed materials are composed of sand or coarser sediment. The greatest variation in silt/clay ratios is associated with samples dominated by silts. In areas of rapid and fluctuating deposition, the lack of temporal and spatial resolution imposed by sample (depth) integration may exacerbate such variations. Silt/clay ratios are likely to be locally similar under relatively high energy conditions (controlling formation of normal D_h and A_l sediments); at such sites, they may reflect composition of the suspended load rather than the deposition of some fraction of it. Silt/clay ratios are most comparable in deepwater (limited circulation) environments subject to low rates of fine silt and clay accumulation. Relationships between silt/clay ratios and sediment mean particle-size in marine and non-marine environments share many similarities.

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References

Damiani, V., 1972. Studio di un ambiente fluvio-lacustre sulla base di una analisi granulometrica dei sediment: Fiume Toce e bacino della Isole Borromee (Lago Maggiore). Mem. Inst. Ital. Idrobiol. 29: 37–95.

Gibbs, R. J., 1985. Settling velocity, diameter, and density for flocs of illite, kaolinite and montmorillonite. J. Sed. Petrol. 55: 65–68.

Grant, A. C., 1970. Distributional trends in the Recent marine sediments of northern Baffin Bay. Maritime Sediments 7: 41–63.

Knight, R. J., 1971. Distributional trends in Recent marine sediments of Tasiujac Cove of Ekalugad Fjord, Baffin Island, N. W. T. Maritime Sediments 7: 1–18.

Kranck, K., 1980. Experiments on the significance of flocculation in the settling of fine-grained sediment in still water. Can. J. Earth Sci. 17: 1517–1526.

Middleton, G. V., 1976. Hydraulic interpretation of sand size distributions. J. Geology 84: 405–426.

Passega, R., 1977. Significance of CM diagrams of sediments deposited by suspensions. Sedimentology 24: 723–733.

Pelletier, B. R., 1973. A re-examination of the use of the silt/clay ratios as indicators of sedimentary environments: a study for students. Maritime Sediments 9: 1–12.

Rosa, F., 1985. Sedimentation and sediment resuspension in Lake Ontario. J. Great Lakes Res. 11: 13–25.

Sandilands, R. G. & A. Murdroch, 1983. Nepheloid layer in Lake Ontario. J. Great Lakes Res. 9: 190–200.

Sherman, I., 1953. Flocculent structure of sediment suspended in Lake Mead. Trans. Am. Geophys. Union 34: 394–406.

Sly, P. G., 1969. Sedimentological studies in the Niagara area of Lake Ontario, and in the area immediately north of the Bruce Peninsula in Georgian Bay. In Proc. 12th. Conf. Great Lakes Res. pp. 341–346. Int. Ass. Great Lakes Res.

Sly, P. G., 1983. Recent sediment stratigraphy and geotechnical characteristics of foreset and bottomset beds of the Niagara Bar. J. Great Lakes Res. 9: 224–233.

Sly, P. G., 1983. Sedimentology and geochemistry of Recent sediments off the mouth of the Niagara River, Lake Ontario. J. Great Lakes Res. 9: 134–159.

Sly, P. G., 1984. Sedimentology and geochemistry of modern sediments in the Kingston basin of Lake Ontario. J. Great Lakes Res. 10: 358–374.

Sly, P. G. (this volume). Sediment dispersion: Part 2, characterization by size of sand fraction and percent mud.

Sly, P. G., R. L. Thomas & B. R. Pelletier, 1983. Interpretation of moment measures derived from water-lain sediments. Sedimentology 30: 219–233.

Thomas, R. L., A. L. W. Kemp & C. F. M. Lewis, 1972. Distribution, composition and characteristics of the surficial sediments of Lake Ontario. J. Sed. Petrol. 42: 66–84.

Thomas, R. L., A. L. W. Kemp & C. F. M. Lewis, 1973. The surficial sediments of Lake Huron. Can. J. Earth Sci. 10: 226–271.

Visher, G. S., 1969. Grain size distribution and depositional process. J. Sed. Petrol., 39: 1074–1106.