GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

BULLETIN 226

PART A: SEDIMENTOLOGY OF PLEISTOCENE GLACIAL VARVES IN ONTARIO, CANADA

PART B: NATURE OF THE GRAIN-SIZE DISTRIBUTION OF SOME PLEISTOCENE GLACIAL VARVES OF ONTARIO, CANADA

Indranil Banerjee

Price, $2.50

Ottawa
Canada
1973

PART A: SEDIMENTOLOGY OF PLEISTOCENE GLACIAL VARVES IN ONTARIO, CANADA

PART B: NATURE OF GRAIN-SIZE DISTRIBUTION OF SOME PLEISTOCENE GLACIAL VARVES OF ONTARIO, CANADA

0,000-1973-0000

Technical Editor
Tamara A. De-Vreeze

Critical Readers
O.L. Hughes
B.C. McDonald

Layout
Leona R. Mahoney
Martha J. McLean

Artwork by GSC Cartographic Unit

GEOLOGICAL SURVEY
OF CANADA

BULLETIN 226

PART A: SEDIMENTOLOGY OF PLEISTOCENE GLACIAL VARVES IN ONTARIO, CANADA

PART B: NATURE OF GRAIN-SIZE DISTRIBUTION OF SOME PLEISTOCENE GLACIAL VARVES OF ONTARIO, CANADA

By
Indranil Banerjee

DEPARTMENT OF
ENERGY, MINES AND RESOURCES
CANADA

Available by mail from Information Canada, Ottawa,

from the Geological Survey of Canada
601 Booth St., Ottawa

and

Information Canada bookshops in

HALIFAX
1687 Barrington Street

MONTREAL
640 St. Catherine Street West

OTTAWA
171 Slater Street

TORONTO
221 Yonge Street

WINNIPEG
393 Portage Avenue

VANCOUVER
800 Granville Street

or through your bookseller

Price: $2.50 Catalogue No. M42-226

Price subject to change without notice

Information Canada
Ottawa, 1973

PREFACE

In order to assist in effective use and conservation of natural resources and in the management and preservation of our environment, the Geological Survey provides geologically-based information on land resources and terrain performance. This report presents some of the results of a study carried out under the auspices of a National Research Council of Canada postdoctoral fellowship at the Geological Survey of Canada.

Most parts of Canada were subjected to several glaciations in the past few million years. The record of these events is best seen in the landforms developed and the deposits formed. Amongst the latter are glacial varves which are rhythmically layered deposits formed in lakes, each layer or varve containing all material deposited during one year.

In the first part of this report the author describes the areal variation and dispersal patterns of varves in several parts of Ontario, their internal structure, and presents a comparison to flysch-type turbidites. In the second part he presents an analysis of grain-size distributions in two suites of varve specimens, one from Glacial Lake Barlow-Ojibway in northern Ontario, and the other from Glacial Lake Iroquois, a forerunner of Lake Ontario.

Y.O. Fortier, Director,
Geological Survey of Canada

Ottawa, June 16, 1972

CONTENTS

PART A

Tables

Figures

Plates

PART B

Tables

Figures

PART A

SEDIMENTOLOGY OF PLEISTOCENE GLACIAL VARVES IN ONTARIO, CANADA

ABSTRACT

Studies of the stratigraphy and sedimentary structures of Pleistocene glacial varves in Ontario reveal that turbidity currents, produced annually by sediment-laden meltwater, have a major role in the formation of varves. Sedimentary structures of the varves studied indicate that, not only as individual layers, but also as a total assemblage and vertical sequence, they contain structures similar to those found in flysch-turbidites.

The coarse (summer) layer of the varves studied occurs in three facies: (1) sandy: thick, sandy silt in proximal varves displaying cross-laminae and grading; deposited by turbidity currents possessing bedloads; (2) silty: thin fine silt in distal varves with single, or multiple graded units; deposited by autosuspension currents; and (3) diamictic: thin fine silt in ultra-distal varves with numerous silt clasts; deposited by mudflow or high-density turbidity currents.

The shape of individual varves was studied by direct tracing of layers and by constructing an isopach map of a particular varve which had been correlated over a wide area. Paleocurrent data from some localities provide a picture of the dispersal pattern.

The existence of "turbidites" in eskers and kame deltas and their lateral passage into crossbedded sand, noted in a few localities, indicate that varve-producing turbidity currents may have originated in delta-fronts. One example of slump-generated turbidity currents depositing varve-like rhythmites in a glacial lake has been noted.

RÉSUMÉ

L'étude de la structure stratigraphique et sédimentaire des varves glaciaires du Pléistocène en Ontario révèle que les courants de turbidité, qui sont produits annuellement par les eaux de fonte chargées de sediments, jouent un rôle important dans la formation des varves. La structure sédimentaire des varves étudiées indique que, non seulement par leurs couches individuelles, mais aussi par leur assemblage global et par leur séquence verticale, elles ressemblent à celles des flyschs affectés par des courants de turbidité.

La couche grossière (été) des varves étudiées présente l'un ou l'autre de ces trois faciés: (1) sableux: un silt sableux, épais, dans les varves proximales à feuillets entrecroisés et agradation granulométrique; mis en place des courants de turbidité à charge de fond; (2) silteux: silt fin, peu consistant, dans les varves distales, avec une ou plusieurs unités granulométriquement; dépose par des courants à autosuspension; et (3) diamictique: silt fin, peu consistant, dans les varves ultra-distales, avec de nombreux débris silteux; déposé par des coulées boueuses ou par des courants de turbidité à haute densité.

La configuration des varves individuelles a été étudiée par levé direct des couches et par la construction d'une carte d'epaisseur d'une varve particulière identifiée sur une grande région. Des données sur les paléocourants de quelques localités donnent une image du réseau de dispersion.

L'existence de "turbidites" dans des eskers et des deltas de kame et leur passage latéral en un sable a stratification entrecroisée, remarques en quelques endroits, indiquent que les courants de turbidité qui produisent des varves peuvent provenir des fronts de deltas. Dans un lac glaciaire, des glissements, probablement à l'origine de courants de turbidité ont laissé des structures qui passent lattéralement à des varves.

INTRODUCTION

The present report is an outcome of a detailed study of Pleistocene glacial varves in Ontario. The statistical part of the study dealing with varves as a time series has been published (Agterberg and Banerjee, 1969). The stratigraphy and the sedimentary structures of the varves and the sedimentation processes involved in their formation are described in this part. Part B of this publication deals with texture of the varves.

In all recent studies on the sedimentology of glacial varves, the role of turbidity currents in the deposition of varves has been recognized (Quigley, 1956, Jackson, 1965, Schenk, 1965 and Latjai, 1967). As far back as 1940, using excellent field data, De Geer concluded that currents operating on a lake bottom deposited varves (De Geer, 1940). Kuenen (1951) later showed that, in most freshwater lakes, sediment-laden meltwater can produce and sustain turbidity currents which are possible agents for the deposition of varves characterized by graded bedding. Further evidence from this study of the stratigraphy and sedimentary structures of the varves supports the turbidite origin of the coarser summer layer (Fig. 2). Data from actual glacial lakes are few. However, Deane (1961, p. 179) reported that in Lake Hazen on Ellesmere Island, the turbid glacial streams flow over the deltas and along the bottom of the lake as density currents. While studying glacial lake sedimentation, Mathews found that both in Lake Garibaldi, B.C. (Mathews, 1956) and in Lake Sunwapta, Alberta (Mathews, 1963) sandy layers are deposited in the deeper parts of the lake by turbidity currents.

Broad features of varve sedimentation that emerge from the present study are: (1) varves show broad similarity with flysch-turbidites both in individual sedimentary structures and total assemblage and vertical sequence; (2) areal variation and facies change in the varves can be explained adequately by the turbidity current mechanism; (3) from the study of deltaic (esker and kame) deposits in the glacial lakes, and particularly from the existence of thicker, sandy 'turbidite' beds in these sequences, it appears that turbidity currents depositing varves have originated on the lower parts of the foreset beds in such deltas. Experimental investigation in deltaic sedimentation by Jopling (1966) has provided the model for such a process. He has explained (Jopling, 1966, p. 75) how high percentages of silt and very fine sand in suspension can hinder the normal growth of foreset slip planes, convert the foreset into a gentle declivity, and change the pattern of flow over the delta into a turbidity current; and (4) besides the turbidity currents produced annually by meltwater, slump-generated turbidity currents also seem to operate in glacial lakes and one example of varves (?) deposited by such currents has been found in this study.

Locations of varve sections studied in Ontario are shown in Figure 1. These include varves of: (1) Lake Barlow-Ojibway (loc. 1 to 11); (2) Ottawa Valley (loc. 12 and 13) - (overlain by marine sand and clay); and (3) Lake Iroquois (loc. 14 to 19 except loc. 17). In many sections, long sequences of varves have been measured and sampled. In a previous study, eight measured series from northern Ontario were analyzed statistically and the method of sampling the varves and of handling the raw thickness data for statistical treatment was also explained (Agterberg and Banerjee, 1969).

Original manuscript submitted: 16 December, 1969
Final version approved for publication: 15 June, 1972

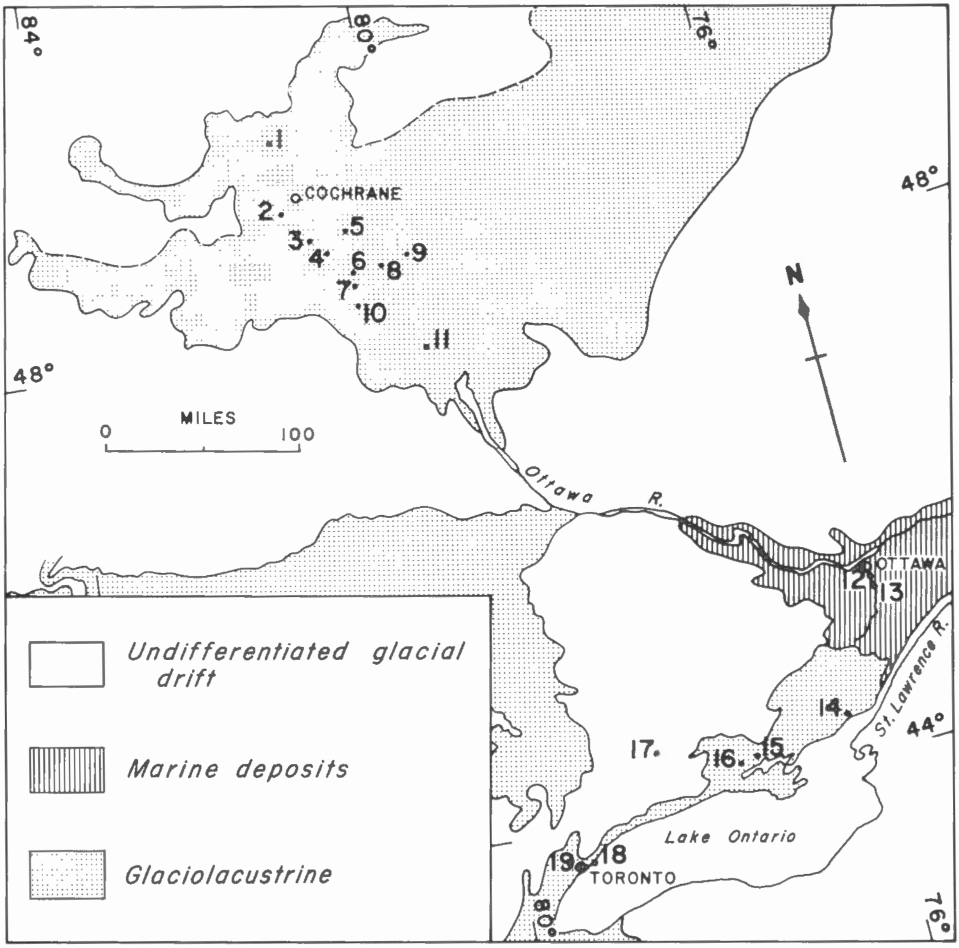


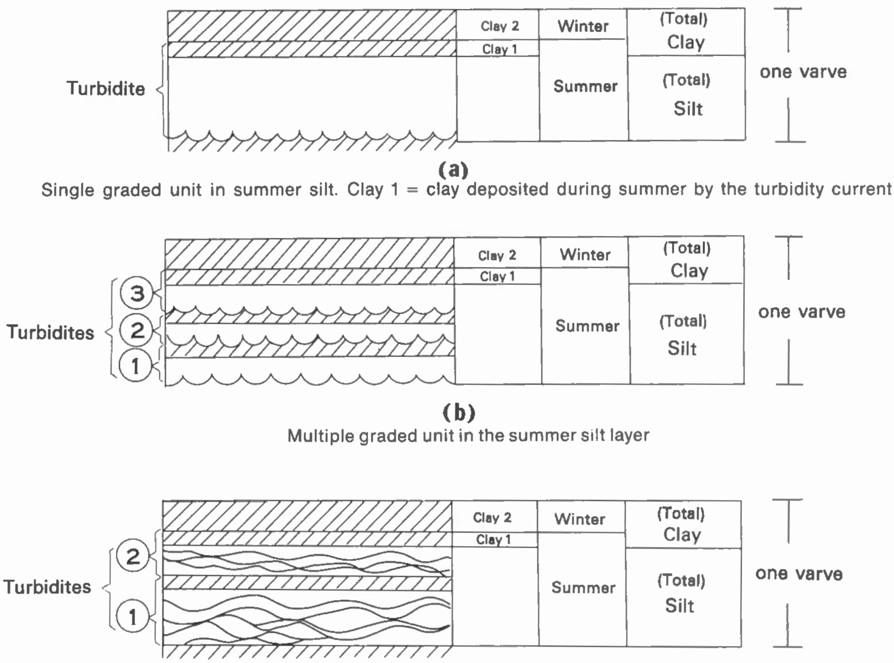
Figure 1. Locations of varve sections. These are shown on the glacial map of the area (after Prest, Grant and Rampton, 1968). At 12 and 13, varves occur below marine clay, at 14 within kame deposits and at 7 and 17 within eskers. Sub-locations of 15 are shown in Figure 4.

Previous studies of varves in the areas mentioned have been made by Antevs (1925, 1928), Hughes (1955, 1965), Quigley (1956) and Lajtai (1967).

ACKNOWLEDGMENTS

This work was carried out at the Geological Survey of Canada with a post-doctoral fellowship from the National Research Council of Canada. Dr. John G. Fyles, Chief, Terrain Sciences Division, was a constant source of help and inspiration throughout the work.

The author gratefully acknowledges the help rendered by Dr. Owen L. Hughes, Geological Survey of Canada, in introducing the author to the varve localities and the able assistance in the field by Mr. Ronald Edwards.



(a)
Single graded unit in summer silt. Clay 1 = clay deposited during summer by the turbidity current

(b)
Multiple graded unit in the summer silt layer

(c)
Cross-laminated and parallel-laminated summer silt layer

Figure 2. Different sedimentation units in typical varves.

Prof. John E. Sanders of Barnard College, Columbia University and Dr. O.L. Hughes and Dr. B.C. McDonald, both of the Geological Survey of Canada, critically read the manuscript. Miss G. Minning, also of the Geological Survey of Canada, made many helpful suggestions.

STRATIGRAPHIC FRAMEWORK

A varve is a conceptual model that includes all material deposited in one year. Glacial varves are commonly couplets that can be divided into a summer part, which is normally silt, and a winter part, which is clay. If the summer layer is considered to be a deposit made by turbidity currents then there is a slight difference between the thickness of total clay and the real thickness of the winter part as shown in Figure 2. Similarly, the silt layer makes up only a portion of the summer thickness.

When a "long" sequence of lacustrine sediments shows regular and repeated alternation of silt (or sand) and clay layers, it has been assumed that each silt-clay couplet is a varve. But when similar couplets occur in shorter sequences within or on top of glaciofluvial sediments, the term "rhythmite" has been used to describe them. Units of single, graded, very fine sand beds passing upward into clay, which the author regards as "turbidites", occur in kames and eskers. According to the model of sedimentation presented here, these can be considered as proximal counterparts of the summer layers of the varves.

The thickness of studied sections varied from 15 to 90 feet. Varves normally occur as a continuous mantle overlying till or, less commonly, the bedrock. Usually the till-varve contact is featureless but, in one place, an intervening layer of gravelly silt with ripple-like bed forms has been noted (layer I, Fig. 5B).

Rhythmites in a deltaic sequence

The relationship between glacial lake sediments and glaciofluvial sediments near the delta front has been studied in eskers and kames. The following significant features are present:

Rhythmites occur mostly near the top of the section at the end of a "fining upward" cycle which starts from gravelly sand at the base. They do not overlie the esker or kame sediments with an unconformable contact but have interfingering and gradational contacts with them (Fig. 3A, D) indicating that the two sediments pass into each other. This is in accordance with the picture presented by earlier workers, that a continuous spectrum of deposits extended from the proximal gravel deposits to the distal lake sediments (which may be varved) and, as the delta-front retreated with time, this lateral facies change produced the "fining upward" cycle (Antevs, 1925; Hughes, 1965).

These rhythmites occur in association with, and locally grading into, sandy, "turbidite" beds that occur in the deltaic sequences of eskers and kames (Fig. 3A, B, C). These beds (Plate 1A) are 30-40 cm thick, the graded beds of medium sand often showing load structures at the base. Similar "kame-delta turbidites" occur near Rensselaer, New York (LaFleur, pers. comm.).

"Turbidite" (graded silt layer with load structures) layers have also been traced directly into foresets of large-scale crossbeds in deltaic sand (Fig. 5C).

The occurrence of sandy "turbidites" in eskers and kames, their gradational contact distally with rhythmites (possibly varves) and their passage proximally into the foresets of crossbedded sand, all indicate that turbidity currents producing the summer layer of the varves may have originated in the delta-front. This is supporting field evidence for the idea that a large amount of suspended sediments flowing over a foreset can produce a turbidity current (Jopling, 1966).

Rhythmites associated with slumps

Besides the normal deltaic situation described above, rhythmites in one locality (loc. 15) have been found in a special setting, namely in association with slumps. Details of the stratigraphy are shown in Figure 4. The bedrock is covered by a thin till which is overlain by varves. Overlying the varves is a slumped layer of laminated silt. This, in turn, is overlain by a mudflow deposit which is composed of structureless silt with pebbles of rocks, clasts of silt and clay, and large fragments of underlying varves embedded in it (Plate 1b). The top unit is a sequence of varve-like rhythmites, each couplet being 5-10 cm thick and each with a silty, cross- or parallel-laminated layer grading into clay above. If these rhythmites are interpreted as deposits of turbidity currents, the sequence suggests that slumping has caused a mudflow which, in turn, produced a turbidity current.

The effects of slumping at a delta-front involving both varves and glaciofluvial sediments is also illustrated in the Rideau River varves (Fig. 9B, loc. 12).

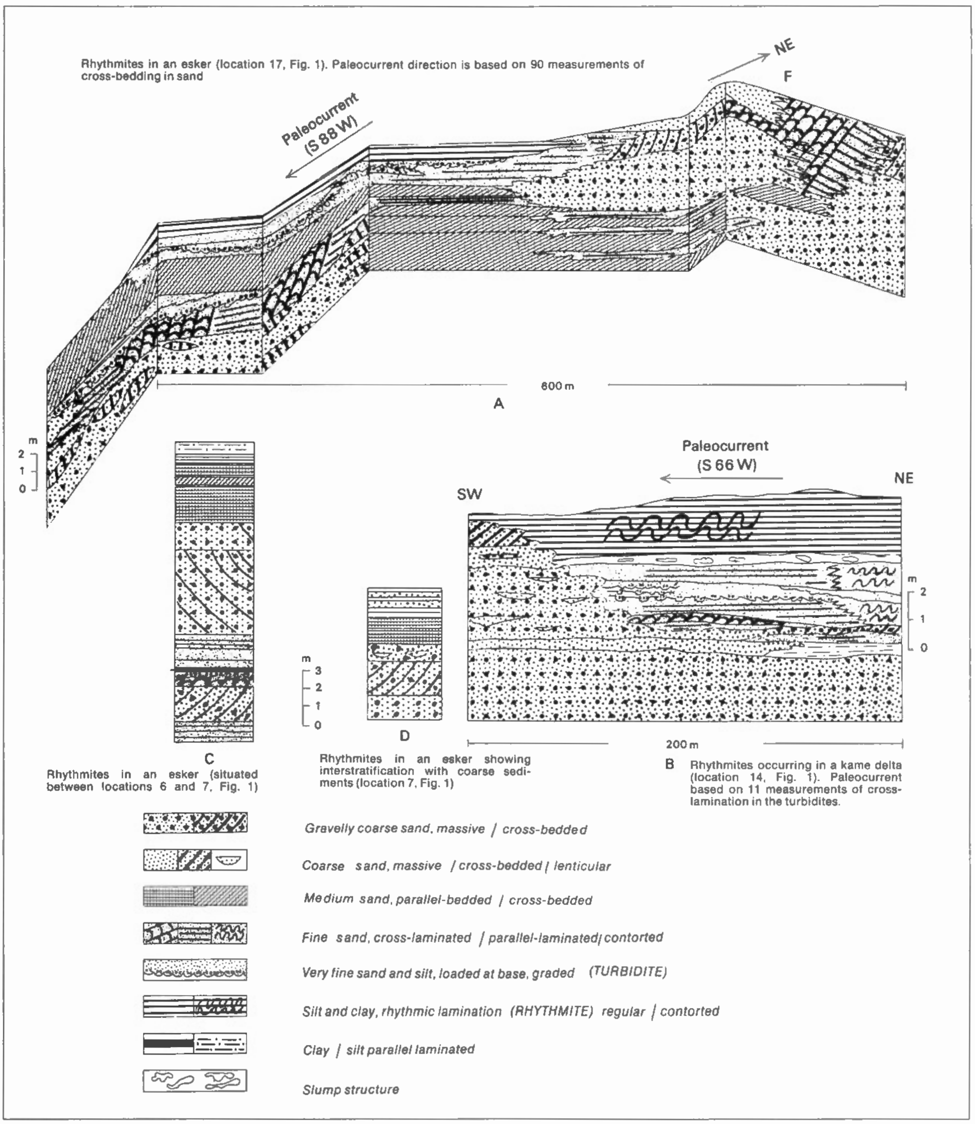


Figure 3. Stratigraphic cross-section of rhythmites in eskers and kames.

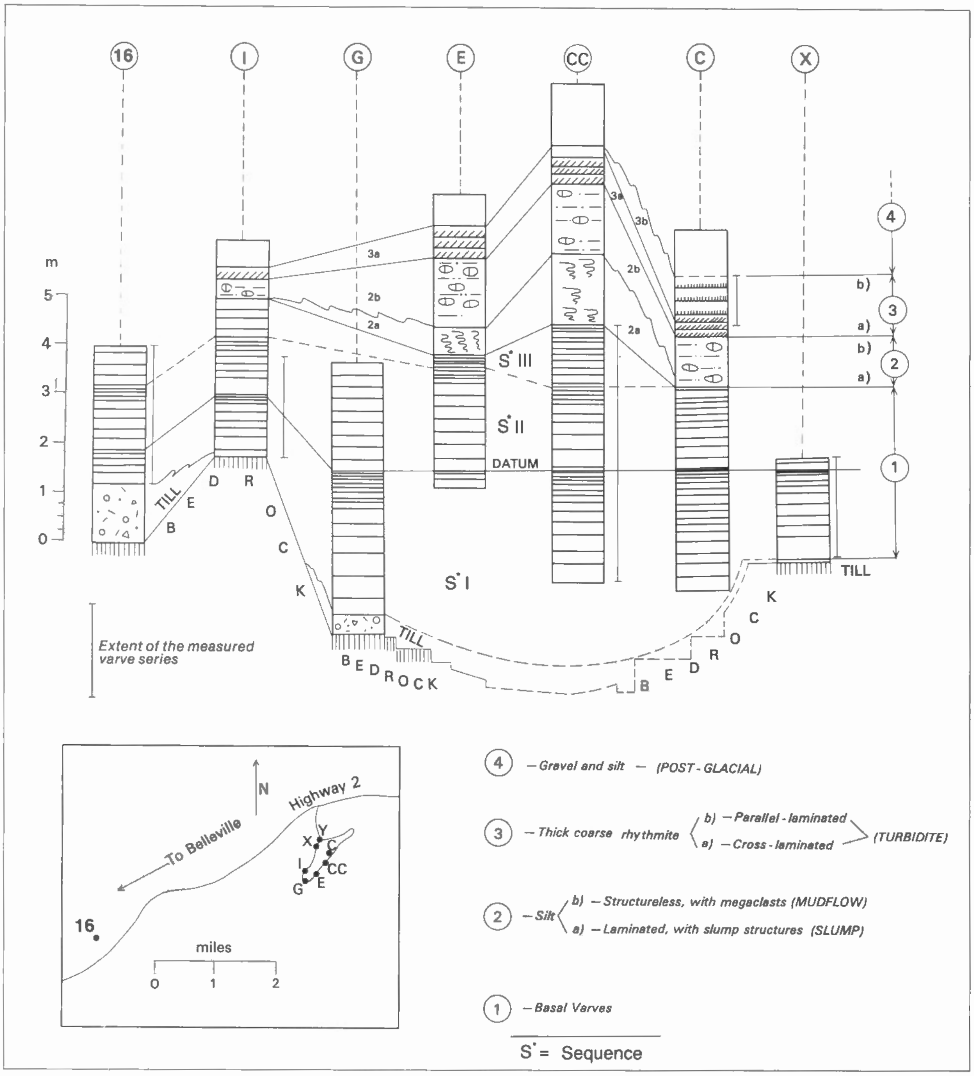


Figure 4. Stratigraphic cross-section of rhythmites associated with slumps. All lettered sections are at location 15. The datum used and the division of the varves into sequences I, II, and III are illustrated in Figure 8. All locations except 16 are in the Canada Cement Company's clay pit at Shannonville, north-east of Belleville, Ontario (loc. 15). Vertical lines beside the columns indicate length of varve series measured.

AREAL VARIATION AND DISPERSAL PATTERN

In northern Ontario thickness data demonstrate that individual varves thin away from the former ice front (Fig. 6).

Isopach map

Although any attempt to correlate a very thin bed (1 to 2 cm) through large distances (60 miles) involves great risk, the base of varve 1528 of Antev's Timiskaming series in northern Ontario is so conspicuous in all varve diagrams that there is some justification in using it as a datum. Hence, an isopach map (Fig. 6) has been constructed from 9 data points compiled from thickness measurements of Hughes (1965) and the present author. The resulting map shows that: a) direction of decrease in varve thickness conforms to the esker paleocurrent but not to the varve paleocurrent, b) the varve paleocurrent is at right angles to the esker paleocurrent. Data points are too few for any unequivocal interpretation, but the over-all shape of the isopachs possibly suggests a multi-lobate shape of the varves as described by De Geer (1940, Fig. 14, p. 75) in the Swedish varves. In the Belleville area (loc. 15 and 16), varves thin away from the ice front in a general southwesterly direction (as seen by comparing the varve diagrams of sections CC, 1 and 16 in Figure 8 and X, 1 and 16 in Figure 5B. In northern Ontario, the rate of thinning is high at first, but it decreases distally (Fig. 6). Due to continuous recession of the ice front, each varve at one locality is overlain by a more distal, hence thinner, part of the next varve. This results in an upward decrease of varve thickness in a section which is found to be exponential in nature (see p. 16).

Lateral continuity of varves

In rare cases, as in the continuously exposed sections of clay pit (loc. 15), varves with a minimum thickness of 2 cm have been traced laterally for a few hundred feet. The silt layers thin rapidly at first but with distance the rate of thinning decreases.

In two instances varves have been followed for a distance of 1 to 3 miles by correlating key beds (Fig. 5A) and by matching varve diagrams (Fig. 5B inset). In both cases, individual varves pinch out and new varves appear in the section within short distances. In Figure 5A, three varves between the key beds have disappeared within a distance of 3/4 miles and in 5B, three new varves have appeared in the section within a distance of 3 1/2 miles.

Although both the examples above show evidence of discontinuity in varves, indirect evidence of lateral continuity of varves over a long distance is also available. This is provided by patterns of thickness change in the varves which show excellent correspondence between distant sections. Two examples follow:

1. In the Barlow-Ojibway varves, a conspicuous reversal of trend in the varve diagrams is noticed in many varve sections. This provides a datum (base of Antev's varves 1528) by which varve patterns in different sections can be matched. Six sections have been correlated by such matching of varve thickness patterns and correlation coefficients for a group of 30 varves have been calculated between each section. The correlation matrix is shown in Table 1.
2. In the second example, from the Belleville area, three sections have been stratigraphically correlated by means of a similar datum, (Figs. 7,

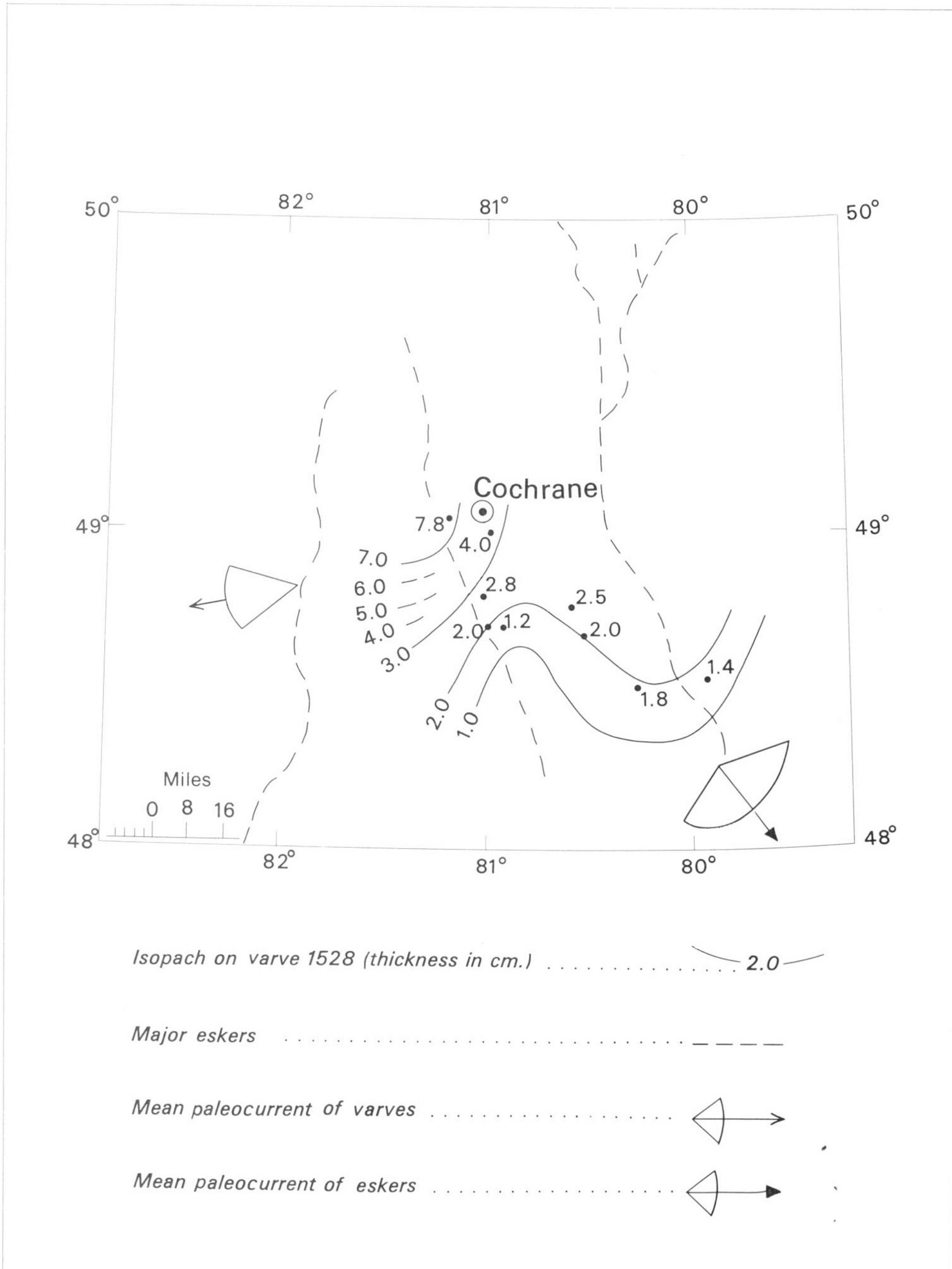


Figure 6. Isopach map of varve no. 1528 of Timiskaming series of Antevs (1928) in Northern Ontario. The lengths of the arcs around paleocurrent directions represent one standard deviation on each side.

8) and the correlation matrix for 51 varves in each section is shown in Table 2. Both examples show a highly significant correlation in patterns of thickness changes of the silt layers. Although this is not a proof of lateral continuity of varves, it is highly suggestive of such continuity. Clay layers in both cases show poorer correlation, the significance of which will be discussed later.

Summarizing the data, it seems that not all proximal, sandy varves are continuous but many distal silty varves are possibly more continuous, as shown in the last example.

Paleocurrent

Sandy or coarse, silty, proximal varves in many cases show cross-laminae from which paleocurrent directions could be obtained. As varve sections are relatively limited in number and layers containing measureable cross-laminations are exposed rarely, the total number of measurements that could be obtained is very small as shown in Table 3. However, the data show a few notable points: (1) two varve localities and the "kame-delta turbidite" show very low standard deviations of the data, indicating a steady undirectional current (turbidity current), (2) the current responsible for deposition of an esker shows wide fluctuations, (3) the greatest scatter occurs, however, in the rhythmites of location 15 where the mean direction is also opposite to the expected current flow along the mean trend of the esker. There, paleocurrent data are probably a mixture of two or more populations yielding a fortuitous mean direction. Relationship of the paleocurrent direction to the shape of the varve, mean trend of the esker, and the paleocurrent direction in the esker has already been illustrated in Figure 6. Many more data are needed before a detailed picture of the dispersal pattern of the varves could be obtained.

Facies change

Facies changes in the varves (Fig. 7) could be best described in terms of the following three facies:

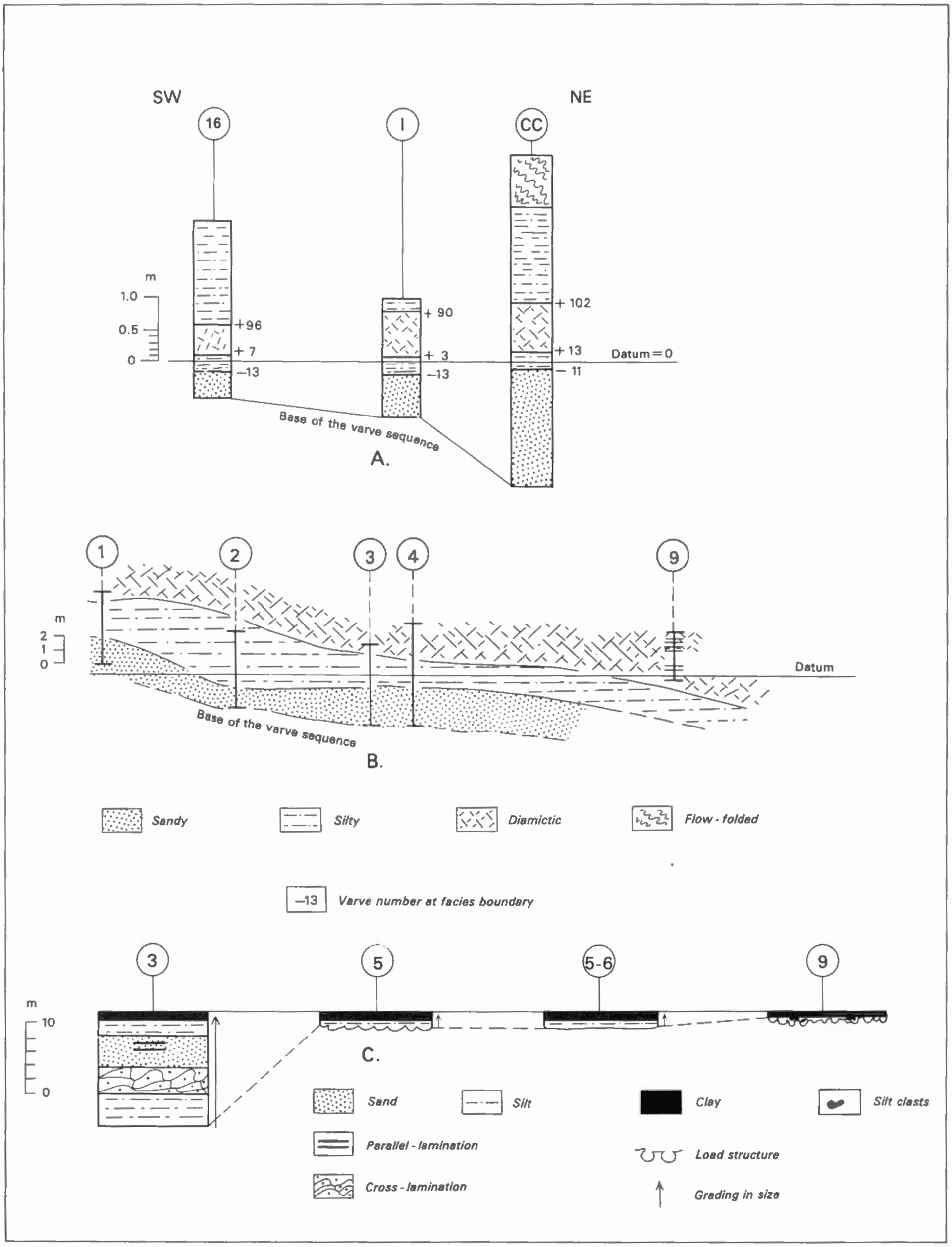
Sandy varves - these are coarser (sand 10 to 20%) and thicker (average thickness - 10 cm) varves with parallel- and cross-laminae, graded beds, and load structures.

Silty varves - these are finer (sand 1 to 5%) and thinner (average thickness - 1 cm) varves with parallel laminae and single, or multiple graded units with load structures.

Diamictic varves - these are the finest-grained varves (sand 0 to 1%) and also the thinnest (0.2 to 0.5 cm). But a few thick (4 to 5 cm) layers may occur exceptionally. Typically a large number of clasts of silt embedded in clay characterizes these varves.

Together with their thickness changes, individual varves also show changes in their texture and internal structure when traced laterally (Fig. 7C) from the proximal to the distal end. Similarly, the gross character of total varve sections also changes with increasing distance from the ice front (Fig. 7B).

In the Barlow-Ojibway varves (loc. 1 to 11) the picture of facies change towards the distal end is from sandy to silty and then to diamictic (Fig. 7B). With the retreat of the ice front, each varve at a given locality is



A. Belleville area (see Fig. 4 for location of lettered sections). Varve numbers given at facies boundaries permit single varves to be followed.
B. Northern Ontario. Numbers on top of sections refer to locations in Figure 1.
C. Facies change of a single varve (no. 1440) in Northern Ontario. Numbers refer to locations in Figure 1. Section 5-6 is located south of location 5 and north of location 6.

Figure 7. Facies change in varves.

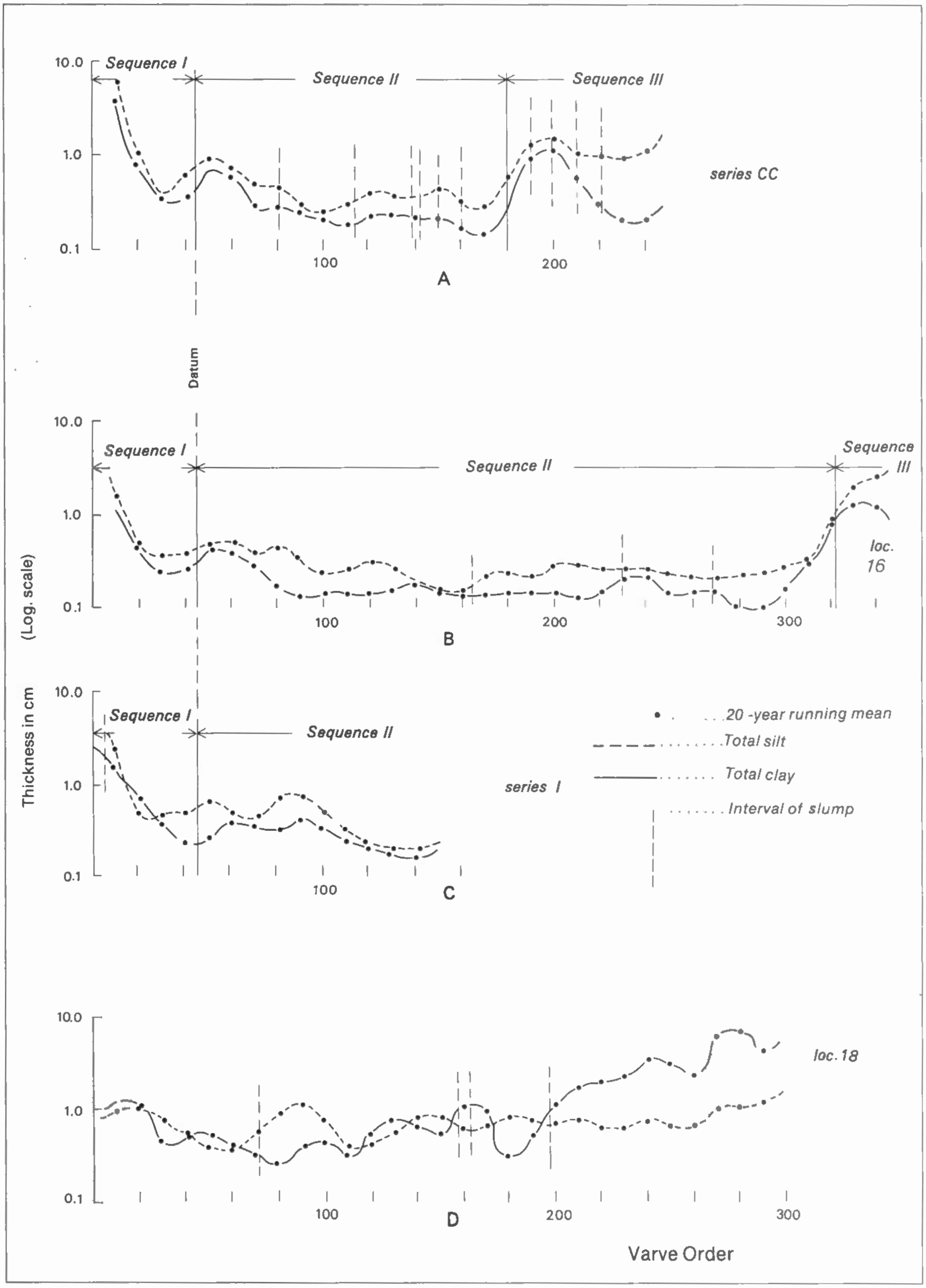


Figure 8. Varve diagrams for four varve series. Linear trend apparent in sequences I of A, B and C. Locations of A, B and C shown in Figure 4. The smaller number of varves in sequence II (138) in series CC compared to those at location 16 (256) is probably due to varves missing as a result of slumping. D - Varve series at location 18. Note larger scatter, very weak linear trend and gradual thickening upwards near the end.

successively overlain by a more distal facies and hence in a vertical sequence the varves change from sandy at the base to diamictic at the top (Fig. 7B). However, examples of interlaminated silty facies occurring within diamictic facies and diamictic varves occurring between silty varves have been noted (Fig. 7A and Section 9 in Fig. 7B). Such departures from the ideal case can be explained either as fluctuations in the ice front (readvance) or as changes due to other factors.

In the Don Valley (loc. 19) diamictic varves are overlain by sandy varves (Fig. 9C). These differ from the diamictic varves of northern Ontario in that they have more regular and thicker layers (average silt = 4.0 cm and average clay = 1.0 cm), parallel lamination, grading near the top, and deformed clasts (Plate 4b). Good examples of channel-fill structures also occur in this group (Plate 1c).

The main differences in structure between the sandy and silty facies are: 1) cross-laminae and parallel-laminae are more common in the former, whereas graded and multiple graded laminae are more common in the latter. Hence, in the deposition of sandy facies, deceleration of the flow was slow enough ("stable phase" of Walton, 1967) for the separation of a bed-load and production of bed-forms. 2) Bedding-plane markings (tool or scour marks) have only been found in sandy varves (Plate 7). The tool or scour marks in the sandy facies mean that, in a few cases, currents depositing them were strong enough to erode the bed. By contrast, in the silty facies, deposition was from an autosuspension current which, during deceleration, did not go through a phase where separation of bed load would take place. In flysch sequences too, Walker (1967, p. 30) has found similar graded ultradistal turbidites (his "A → E beds") less than 3 cm thick.

The facies of varves described here as "diamictic" is not peculiar to occurrences in Ontario. Similar varves have been described from the Swedish sequence by De Geer (1940, Pl. 50) (who described tham as ultradistal "microvarves with microboulders") and by Quigley (1956) from the Connecticut Valley, U.S.A. In all these occurrences, the facies is characterized by its ultradistal position, very small thickness and presence of numerous silt clasts. "Ice-rafting" of the clasts does not seem to be an adequate mechanism to explain the origin of these features, because it cannot explain the derivation and uniform composition of the clasts nor the distal position of the facies. Hughes (1965) interprets these clasts as products of wave erosion and shallow water deposition. But the texture of the varves which show the clasts floating in a clayey matrix (Plate 9b and c) cannot be produced by such a process. Both the texture (e.g., high matrix: grain ratio and disrupted framework) and the derivation of the clasts can be best explained by postulating a mudflow or a high-density, turbidity-current origin for this facies. The distal position can be a result of the higher velocity of such flows which might have enabled them to by-pass the main turbidity flow and to deposit their load at the distal end.

Facies relationship in the varve section (Fig. 9A; loc. 18 = loc. A1106 of Karrow, 1967) studied in the Scarborough Bluffs is unique in the following ways:

(i) Basal varves do not belong to the proximal sandy facies but to the silty facies followed upwards by cross-laminated sandy facies. This may mean that there was an ice-readvance causing deposition of pro proximal varves on top of more distal varves.

(ii) The uppermost varves are characterized by very thick clay (winter) layers. The thick clays are possibly deposits of ultradistal parts comparable to the pelagic deposits of flysch basins (Dzulynski and Walton, 1965, p. 237, Fig. 161E). Most of the turbidite laminae (the silt layers) wedge out before they reach such a long distance. Hence, the thick clays represent deposits of many years rather than that of a single year.

INTERNAL STRUCTURE OF THE VARVES

Individual structures

Varves show a variety of current-generated sedimentary structures which are confined to the silt layers. The only structure shown by the clay layers is faint parallel lamination and a strong preferred orientation of the clay minerals. In the following discussion of the sedimentary structures, the individual structures will be described separately, and then the total assemblage of the structures and their vertical sequence will be discussed and their significance evaluated.

Grading: The following significant features have been observed in the graded silts in the varves:

Commonly, a single silt layer is a multiple graded unit consisting of approximately 7 to 8 graded units (Plate 2c and Plate 5a) each of which normally shows load structures at the base. These occur typically in the silty facies. Single, homogeneous, graded units showing a complete vertical gradation in mean size from silt at the bottom to clay at the top are rare (Plate 2a).

Many individual graded units have laminated tops (Plate 2b and c). These units, together with load structures (which may be deformed sole marks) at the base, are typical "turbidite" sedimentation units on very small scale (Kuenen, 1964).

Parallel lamination in many cases co-exists with size-grading, and in many laminated and cross-laminated units in sandy varves there is an overall gradation in size merging into clay at the top (Plate 3d) and indicating deposition from a decelerating current.

Cross-laminae: In the sandy facies, crosslamination is a common structure in the coarse layer and, in the silty varves a few occurrences of micro-cross laminated (0.1 cm thick) units have been noted near the top of graded silts (Plate 2c). Where ripple-forms in the cross laminae have been fully preserved, the measured ripple-heights vary commonly from 1.0 to 2.0 cm, the maximum recorded being 5.5 cm and ripple-lengths vary from 10 to 18 cm. Ripple-geometry changes from types with full stoss-side (Type A) erosion, through those with fully preserved stoss-side (Type B) to "sinusoidal" ripples (nomenclature of Jopling and Walker, 1968). An example of evolution of types in a vertical sequence is illustrated in Plate 3a. Isolated ripples with internal laminae and embedded in clay (Plate 3b) is also a common feature. Large "sinusoidal" ripples in poorly-sorted, gravelly, very fine sand lying at the base of the varve sequence (proximal turbidites?) have been found in two places. In one case (Fig. 5b), the ripple-height is 13 cm and the ripple length is 45 cm and in the other case (Plate 3e) they are 5 cm and 39 cm respectively. In the latter case they are followed by sinusoidal ripples in varves.

Parallel laminae: This is ubiquitous in all the facies of varves. Perhaps this is an omnibus grouping which includes structures of many different origins. For example, individual units in multiple graded silt layers, if sufficiently thin, may each be considered a lamina. Similarly, cross-laminae formed by very low amplitude ripples may also appear as parallel laminae (Plate 3d).

Channel-fill: A series of channels (Plate 1c) cut into and filled in by diamictic varves has been found in the Don Valley section (loc. 19). Some of these are characterized by a lag deposit of large broken fragments of varves at the base and faulted side walls. A microscopic channel 2 mm wide and 1 mm deep, has been found to cut into the underlying laminated sediments in a silty varve (Plate 5d). This is very similar in appearance to the cross-section of a flute mark (cf. Dzulynski and Walton, 1965, Fig. 31A, p. 46).

Load structures: Load structures with clay flames (Plate 5a) at the base of the graded units are very common in the silty varves. Thin diamictic varves also show loads at their base. Under the microscope, load pockets are seen to be filled with coarser grains (Plate 5c). They also show disrupted lamination (Plate 5b) and extreme deformation (Plate 6d).

Deformational structures: Slump structures in the varve sequences (Plate 6a, and b) occur at all scales from slumped layers measured in miles (Fig. 3) to those confined to microscopic layers. Flowage folding due to load deformation (Plate 6d) and contorted laminae (Plate 6c) are also common.

Current lineations: In unconsolidated sediments such as varves, sole marks are difficult to observe, although it is believed that many load structures seen in cross-section are actually sole marks affected by loading. One reason for this belief is that, in a rectangular block, load structures occurring in two opposite faces match very well both in dimension and spacing, indicating that they are cross-sections of a linear feature. A few linear features found along bedding planes are illustrated in Plate 7. The micro-channels in Plate 5d may be flutes in cross-section.

Trace fossils: Burrow-fills seen mainly in cross-section (Plate 8a to e) are very common in both sandy and silty varves. As these frequently cut across laminations, a post-depositional origin is indicated. It has been noted that, in turbidity current sedimentation, burrows of a particular type do not occur in layers thicker than a certain value (Seilacher, 1962). Although no systematic study has been done, it has been observed that burrows of one type (Plate 8a) are absent in thicker layers.

COMPARISON TO FLYSCH-TYPE TURBIDITES

Taken as a whole, the common association of structures found in the varves: i.e., graded bedding (simple and multiple), cross-, parallel- and contorted laminae, load structures and overall rhythmic alternations of silt and clay, is similar to or identical with that found in the flysch turbidites.

Even though the turbidity-current origin of the summer layer of varves has been accepted by many workers in the field since it was first proposed by Kuenen (1951), there is a hesitancy among geologists to compare them directly to the better known flysch-turbidites, mainly for the following reasons:

1) The graded silt layers of varves are believed to be deposited by "steady" currents (Jopling and Walker, 1968; Latjai, 1967) as opposed to "spasmodic" turbidity currents which supposedly have deposited the flysch sediments. However, it may be instructive to compare the sedimentary structures in varves to those found in flysch turbidites to see whether a "steady" current does differ significantly from a "spasmodic" current in the mechanics of deposition. Again, there are evidences suggesting that slumping occurs frequently during varve sedimentation and that some varves (?) are produced by slump-generated spasmodic turbidity currents. The resulting varves are similar to adjacent varves in the sequence.

2) Silt layers in varves are generally much thinner and finer-grained than flysch-turbidites, suggesting that a special kind of low-velocity and low-density turbidity current deposited them. In general, this is probably true but there are thick varves and, contrary to common belief, many flysch-turbidites are very thin. For example, according to McBride, in the Martinsburg Formation "over 60 per cent of the units (turbidites) are less than one inch thick" (McBride, 1962, p. 49). Some thickness data of flysch beds are listed in Table 5 and they have a large overlapping range with the varves (Table 4), although the varves have yet to undergo an unknown amount of compaction.

Hence, a valid case for comparing structures of flysch-turbidites and varves seems to exist, and in Tables 6 and 7 a very gross comparison has been attempted. The former compares the total assemblage of structures and the latter the vertical sequence in terms of Bouma's model (Bouma, 1962).

None of the comparisons provides any conclusive evidence. For example, in total assemblage, there is much divergence among the flysch-turbidites themselves. Parallel-lamination seems to be the most common structure in one sequence (column III, Table 6) and graded beds are very rare. But in another sequence (column IV, Table 6) graded beds with parallel lamination seems to be the most common structure. The varves seem to occupy an intermediate position between these two extremes.

In vertical sequence, the varves differ from the Bouma model in two respects: first, a-e type of complete sequences are very rare, and second, d-e sequences are the most common, whereas in Bouma's own data, c-e sequences seem to be most frequent. Yet the a-e sequence of Bouma's model is not common among turbidites, as quantitative studies show a wide range of variation in the vertical order of structures in flysch turbidites (Walker, 1967). An explanation for the failure of cross-lamination (c-interval) to form in the varves could be the predominance of silt sizes. In an experimental study, (Rees, 1966) ripples in silt have been found to be the stable bed-form in a particular stress range and, even in that range, plane bed (parallel-lamination) could become the stable bedform if the suspension load is high enough. Thus, a large suspension load, which the varve-producing currents probably had, can suppress the formation of ripples in silt.

To summarize the data of sedimentary structures from varves:

(1) The same assemblage of internal structures occurs in varves as in the better known (flysch) turbidites. The only exception is the rarity of sole marks in varves which are difficult to observe in unconsolidated sediments. However, the author believes that a thorough search in a locality such as Scarborough Bluffs (loc. 19) will yield many examples.
(2) The difference in the scale of thickness between varves and flysch-turbidites is not significant. There are many thin turbidites.
(3) Neither the relative abundance of different structures nor the vertical order in which they occur are consistent in flysch-turbidites so that a comparison of these aspects to those in varves is not instructive.
(4) The common occurrence in varves of the turbidite sedimentation unit, a graded bed with an upper laminated unit and load structures (probably loaded sole marks) at the base, shows that "spasmodic" and "steady" turbidity currents probably have similar depositional histories.

QUANTITATIVE STUDY OF VARVE THICKNESS

As mentioned earlier, the statistical part of the present study dealing with the varve thickness data has already been published (Agterberg and Banerjee, 1969). Some additional data will be included here, followed by a brief discussion.

Four newly measured varve series are shown in Figure 8. In sequence I of series CC, 16 and I varve thickness decreases exponentially upwards (Plate 1d). This trend has been interpreted as the result of exponential thickness profile of individual varves and gradual retreat of the ice front. Reversals of this trend occur near the end of two series (Fig. 8A, B) probably indicating short periods of ice readvances.

From the previous study (Agterberg and Banerjee, 1969) as well as from the data presented here, it has been noted that silt layers differ from clay layers in: a) being more variable in thickness (Table 4); b) having a more conspicuous linear trend (Fig. 8); c) having thicknesses with much less relation to thicknesses of layers deposited several years ago than in the case of clay layers; and d) showing better correlation between sections than does clay (Tables 1 and 2). The latter means that silt layers have more "individuality", or a more distinctive thickness profile peculiar to each layer. All these points taken together would conform to the theory that silt is deposited during short-lived, random events (turbidity currents) whereas the major part of the clay (clay 1 of Fig. 2) is deposited continuously over a much longer period of time.

It has been claimed that a characteristic feature of turbidite beds (of flysch basins) is the log-normal nature of their bed-thickness distributions (Bokman, 1953, Nederlof, 1959, and McBride, 1962). One author (Nederlof, op. cit.) went even further by claiming that "turbidites" can be distinguished from glacial varves by the log-normality of the thickness distributions of turbidites. A few log-normal bed-thickness distributions found in varves (Fig. 10, 1C and 1S) show that this is not true. Actually, applying log-normal distribution to data which show any time-trend is meaningless, and time-trends in turbidite series have been detected by many workers (Nederlof, 1959;

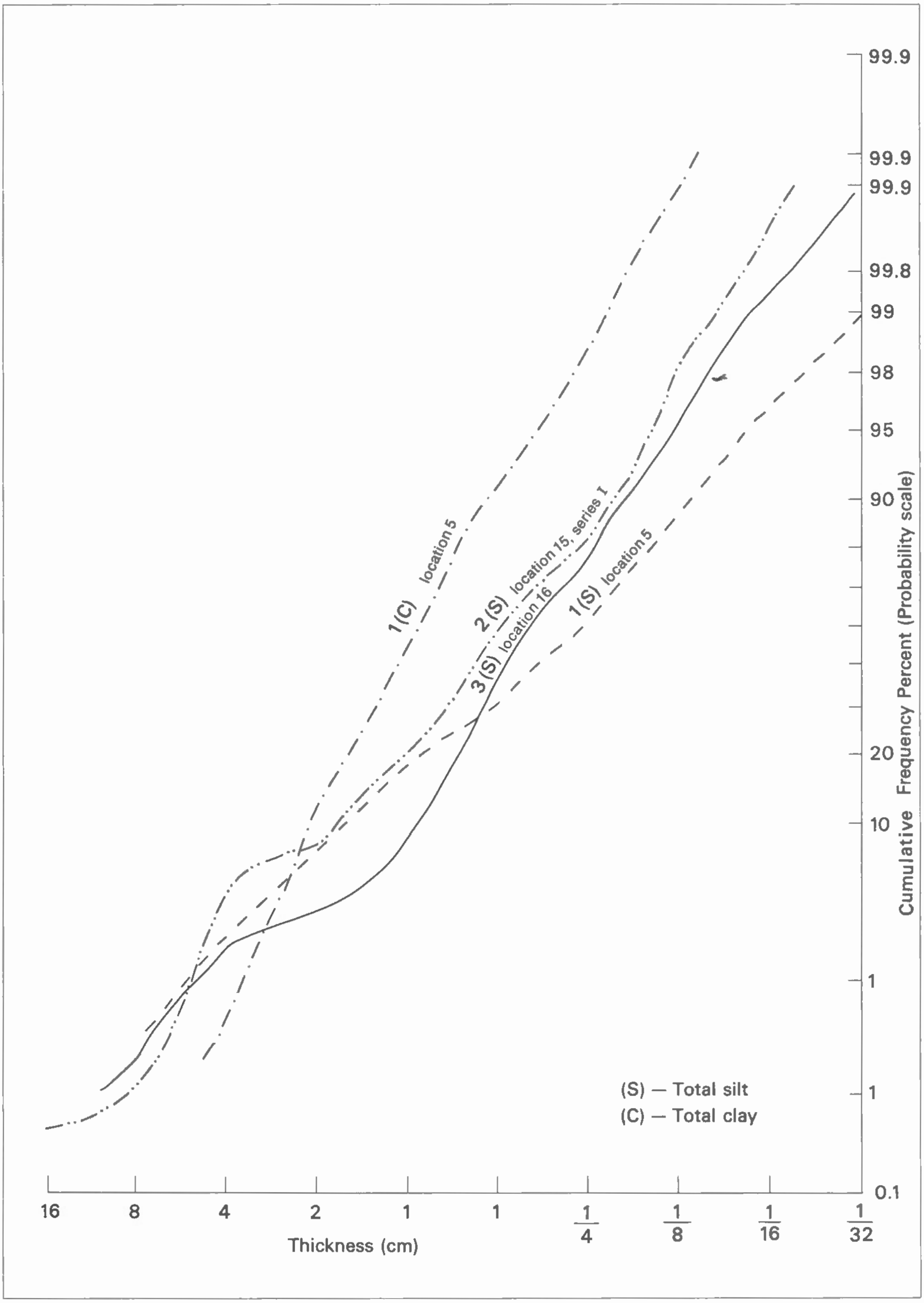


Figure 10. Cumulative frequency distributions of some varve thickness data plotted on a log-probability scale.

Kimura, 1966; and Vassoyevich and Bezhayev, 1961). Because the varves have strong time-trends, the plot of thickness distribution of a varve series is not meaningful either. The curves in Figure 10 have only been included for comparison with similar curves of turbidites that have been published previously.

It has also been found in this study that the thicknesses of silt and clay layers show significant statistical correlation because both show the same time-trend. Perhaps this holds true in many flysch-turbidites as well. Hence, any genetic (hydrodynamic) interpretation given to a significant correlation between thickness of sandstone and shale beds in turbudites, might be misleading.

CONCLUSION

(1) The coarser silt layers of varves are deposited by periodic turbidity currents caused by sediment-laden meltwater entering glacial lakes as proposed by Kuenen (1951). Multiple graded beds in the silt (summer) layer suggest that there was more than one flow, and perhaps 7 or 8, per season. Whether such turbidity flows were spasmodic or steady cannot be determined from the evidence of the sedimentary structures.

(2) The silt layers in varves are similar in many respects to flysch-type turbidites. The thickness and the assemblage and vertical succession of sedimentary structures in the two groups compare very well. Although the ideal Bouma sequence does not occur frequently, the basic turbidite unit with a "graded base and laminated top" (Kuenen, 1964) is common.

(3) The gradational relationship between rhythmites, "turbidites" and glaciofluvial deltaic sediments has been studied. Thin graded silt layers or "turbidites" have been traced into the foresets of cross-bedded esker sands in one case (Fig. 5C). Such a relationship confirms De Geer's (1940, p. 52, 53) picture of esker-sedimentation in which esker sands laterally grade into proximal varves which, in turn, grade into thin distal varves.

(4) This gradation from deltaic sand to lacustrine turbidite and finally to the summer layers of varves also demands a change in the mechanics of sedimentation near the delta-front. Obviously, near the toe of the foresets normal tractive currents gave rise to turbidity currents which flowed into the lake bottom.

(5) Apart from the periodic turbidity currents, there are evidences for non-periodic slump-generated turbidity currents. In one example, a vertical sequence provides evidence of a slump developing into a mudflow which, in turn, produced a turbidity current. Thicker turbidites deposited by such slump-generated currents have been described from ancient glacial sediments (Banerjee, 1966). In modern glacial lakes the existence of slumps producing turbidity currents has been suggested by Mathews (1956).

TABLE 1

Correlation matrix of Northern Ontario varves

Silt (Summer)						Clay (Winter)					
	3	4	5	6	9		3	4	5	6	9
3		0.7848	0.7633	0.7881	0.6724	3		0.6415	0.5119	0.7961	0.2957
4			0.7853	0.7211	0.7955	4			0.7651	0.5881	0.6065
5				0.6091	0.6525	5				0.3313	0.7196
6					0.5760	6					0.1796
9						9					

Numbers at the top refer to locations of varve series shown in Figure 1.

TABLE 2

Correlation matrix of Belleville varves

Silt (Summer)				Clay (Winter)			
	1	2	3		1	2	3
1		0.794	0.824	1		0.713	0.538
2			0.893	2			0.453
3				3			

1 - Section 16, 2 - Section 1, and 3 - Section CC, all shown in Figure 3.

TABLE 3

Paleocurrent data of varves and associated beds

	Location (on Fig. 1)	Sediment types	No. of observ.	Direction		Expected current direction
				Mean	Standard Dev.	
1	1, 3 and 5	Sandy varve	15	255°	27.2°	SSE*
2	15	Sandy abnormal varve	16	52°	104.4°	SW*
3	18	Sandy varve	10	158°	17.9°	SSE**
4	7 and between 8 and 9	Esker sand	82	143°	71.4°	SSE*
5	14	Kame delta turbidites	11	246°	32.9°	SW*

* - From mean trend of eskers

** - At right angles to the shoreline of lake

TABLE 4

Thickness data of the varves

Sr. No.	Series	No. of observ.	Silt Mean (in cm)	Silt S.D. (in cm)	Silt Co. Var S.D./Mean	Clay Mean (in cm)	Clay S.D. (in cm)	Clay Co. Var. S.D./Mean
1	Loc. 1	156	2.34	4.80	2.05	2.52	1.33	0.52
2	Loc. 2	34	13.31[1]	24.24	1.83	1.57	0.87	0.55
3	Loc. 3	239	2.04	3.42	1.67	1.10	0.40	0.36
4	Loc. 4	158	0.62	0.42	0.68	0.72	0.32	0.44
5	Loc. 5	537	0.85	1.32	1.55	1.15	0.78	0.68
6	Loc. 6	160	0.58	0.38	0.66	0.81	0.37	0.46
7	Loc. 8	277	1.02	1.17	1.15	1.17	0.44	0.38
8	Loc. 9	323	0.28[2]	0.19	0.68	0.75	0.35	0.47
9	Loc. 11	316	1.52	0.43	0.28	2.11	0.70	0.33
10	Loc. 16	341	0.44	0.65	1.47	0.29	0.51	1.76
11	CC*	246	1.05	2.50	2.38	0.55	1.21	2.20
12	I*	145	0.73	1.34	1.84	0.43	0.72	1.67
13	Loc. 18	298	0.79	0.90	1.14	1.88	4.97	2.64

All locations on Figure 1 unless marked otherwise

* - Locations shown in Figure 3

1 - Sandy proximal varves

2 - Diamictic and silty distal varves

S.D. = Standard deviation

Co. Var. = Coefficient of variation

TABLE 5

Thickness data of flysch-turbidites

Formation	No. of observ.	Sandstone			Shale		
		Range (in cm)	Mean (in cm)	S.D.	Range (in cm)	Mean (in cm)	S.D.
Haymond[1], Texas, U.S.A.	768	0.5-42.0	4.0	5.2	0.1-42.0	4.9	3.0
Martinsburg[2], New York, U.S.A.	578 (ss) 411 (sh)	0(?)-50.0	1.25*	x	0(?)-10.0	0.23*	x
Up. Carboniferous[3], Spain	364	0.5-35.0	1.00*	x	0.5-81.0	3.50*	x

1 Dean and Anderson (1967)
2 McBride (1962)
3 Nederlof (1959)
ss = sandstone

sh = shale
x = not reported
*Median thickness read from published cumulative curve

TABLE 6

Comparison of types of structures in varves and flysch-turbidites

Types of internal structures	Percentage of different types			
	I (n = 579)	II (n = 61)	III (n = 450)	IV (n = 578)
Parallel lamination	46.2	11.5	71.0	3.0
Parallel and cross lamination	x	6.6	18.6	1.0
Cross lamination	4.0	24.5	2.6	3.0
Graded simple	7.6	32.7	2.6	38.0
Graded multiple	16.2	6.6		
Graded and parallel lamination	3.3	x	5.3	x
Graded, parallel and cross lamination	x	11.5	x	44.0
Contorted lamination	16.8	x	x	7.0
Structureless	5.9	6.6	x	3.0

I. Glacial varves fron Ontario, Canada, (locs. 4, 5, 15, Fig. 1)
II. Istebna beds, Carpathian Flysch, Poland (Unrug, 1963)
III. Lgota beds, Carpathian Flysch, Poland (Unrug, 1959)
IV. Martinsburg Formation, Central Appalachians, U.S.A. (McBride, 1962)

TABLE 7

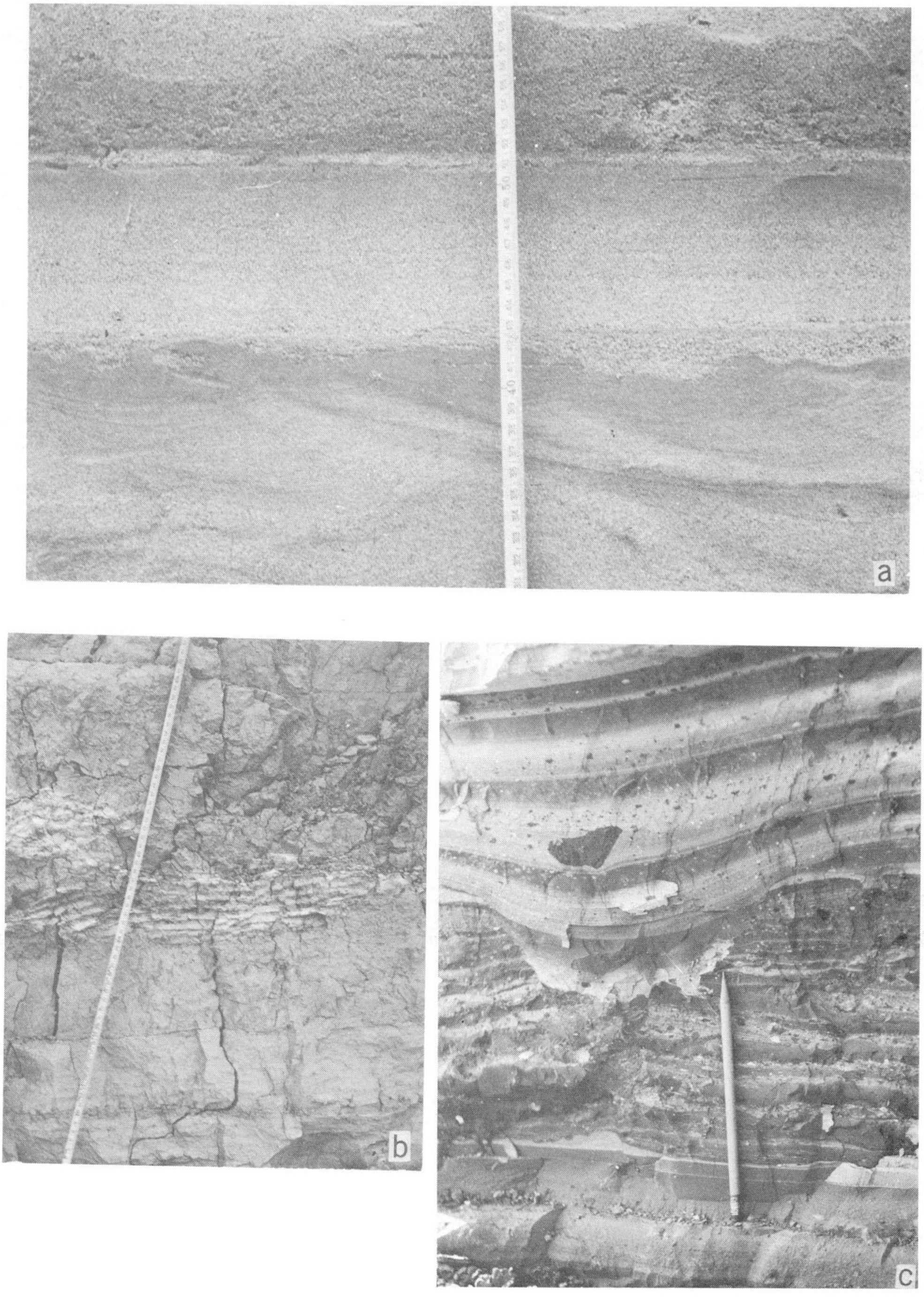
Sequence of internal structures in varves and flysch-turbidites

Bouma's model

e. Pelitic interval
d. Upper interval of parallel lamination
c. Interval of ripple lamination
b. Lower interval of parallel lamination
a. Graded interval

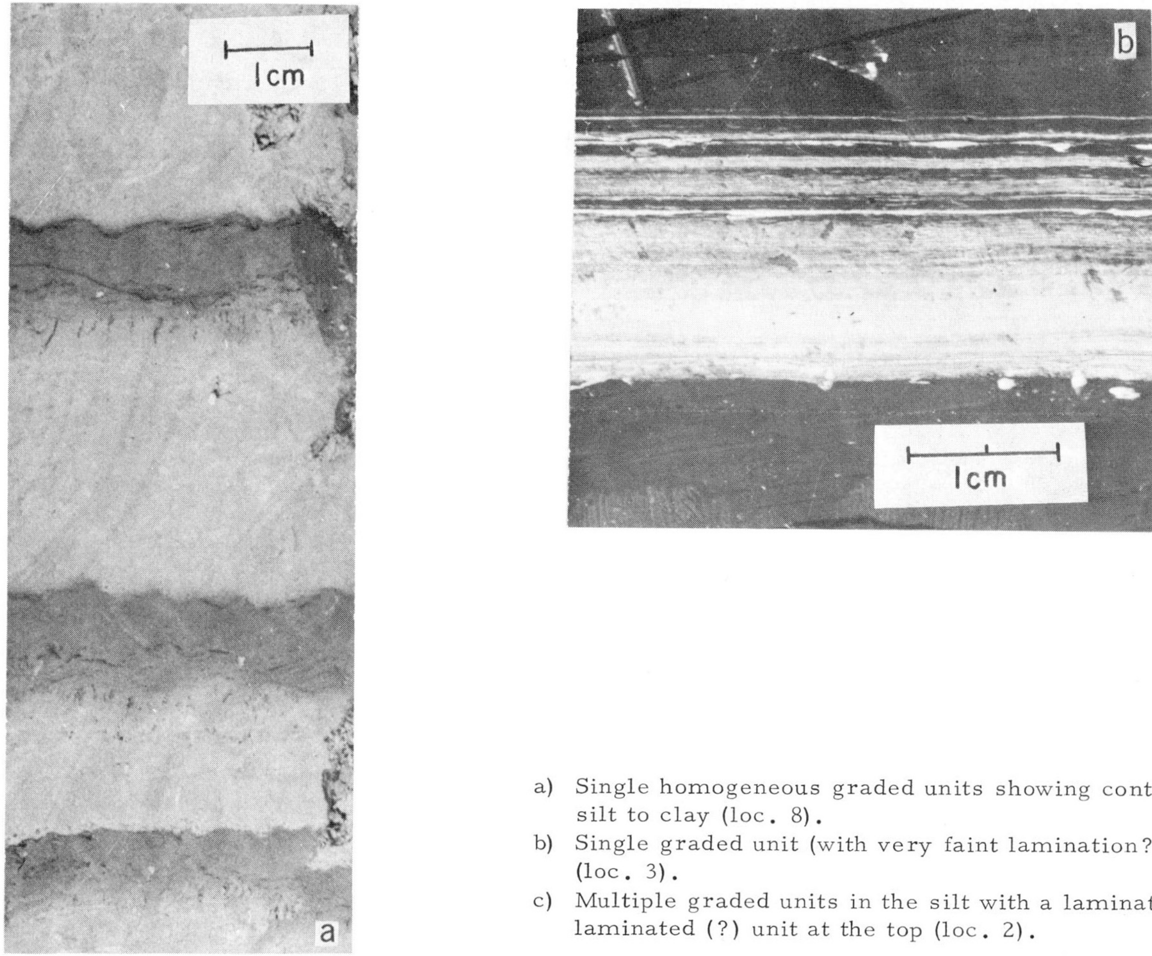
Types of sequence	Percentage of different types	
	I n = 173	II n = 1061
a-e	1.1	10.0
b-e	4.6	8.7
c-e	4.6	64.5
d-e	51.4	6.8
c-d	2.9	
a-b, e	11.6	10.0
b-c, e	10.4	
others	13.3	

I. Glacial varves from Northern Ontario (locations 1, 3, 5, Fig. 1)
II. Flysch turbidites from Maritime Alps, France (Bouma, 1962)


a
b
c

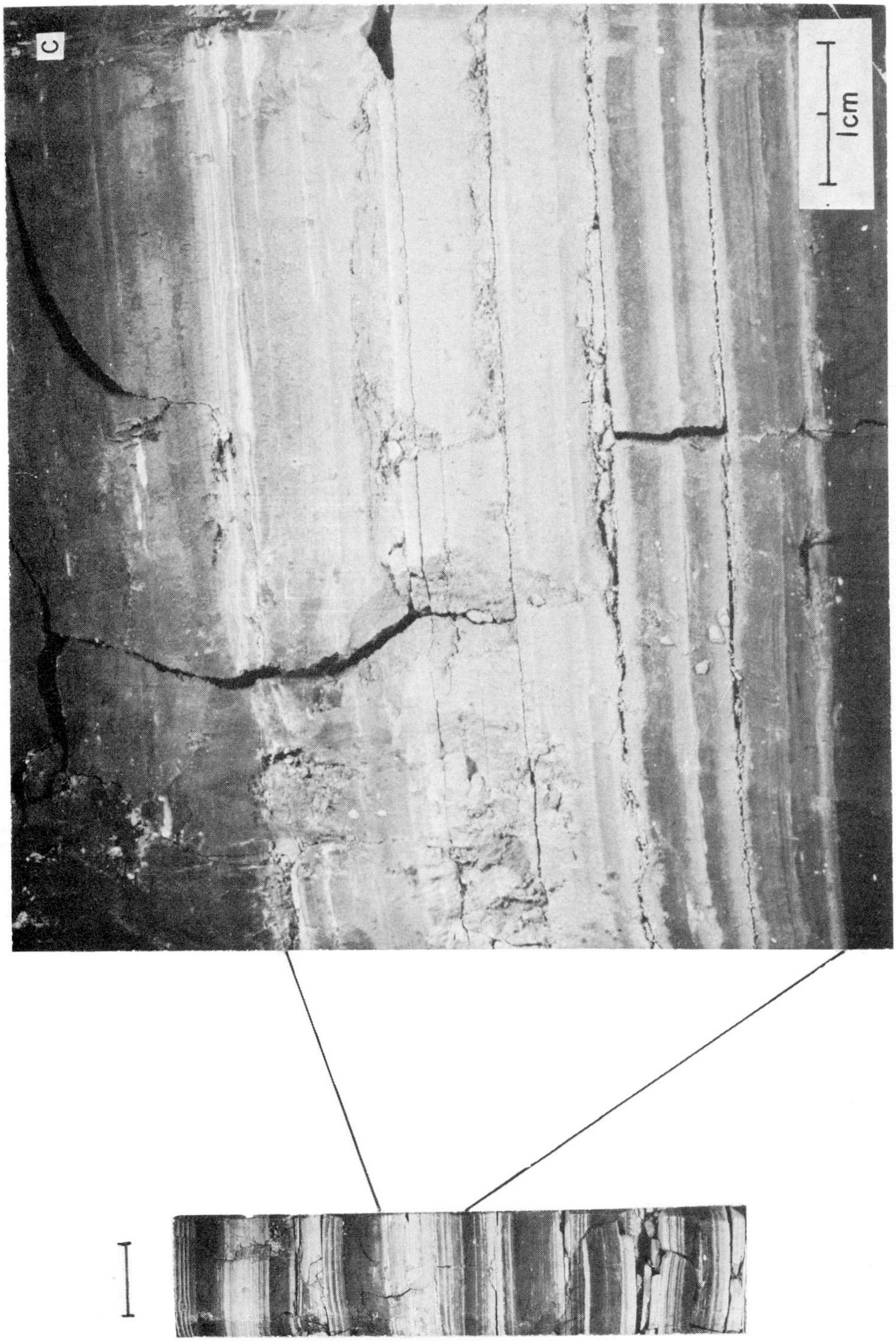
a) Turbidites in the kame deposit (loc. 14) Ontario. Scale in cm.
b) Fragments of underlying varves embedded in structureless silt (mudflow deposit) in the clay pit at location 15. Scale in cm.
c) Channel cut into diamictic varves and filled in with diamictic varves in the Don Valley Brickyard, Toronto (loc. 19).
d) Thinning upwards of basal varves of sequence I (see Figs. 4 and 8) seen in the clay pit at location 15. Scale in inches.

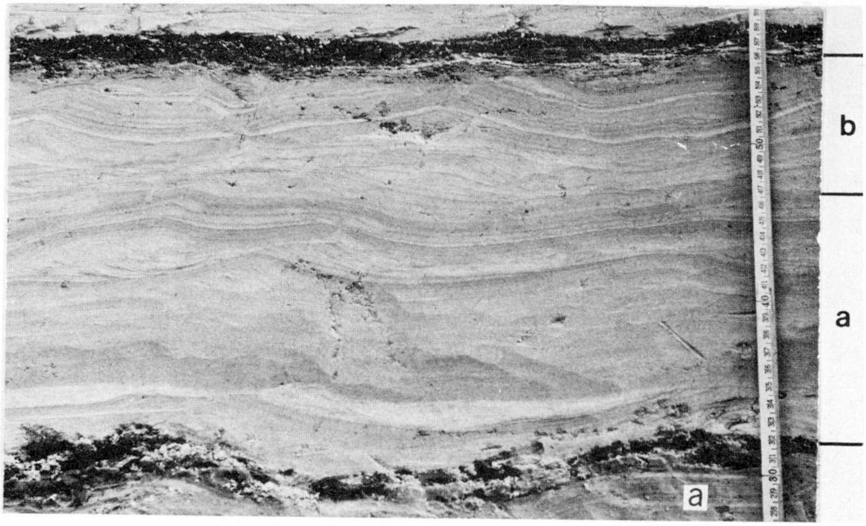
Plate 1. Large-scale features of varves

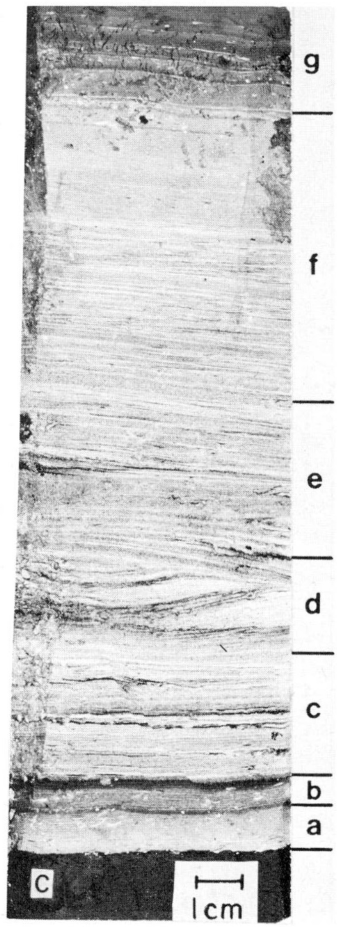


a) Single homogeneous graded units showing continuous grading from silt to clay (loc. 8).
b) Single graded unit (with very faint lamination?) with laminated top (loc. 3).
c) Multiple graded units in the silt with a laminated and cross-laminated (?) unit at the top (loc. 2).

Plate 2. Nature of graded beds in varves (silty facies).

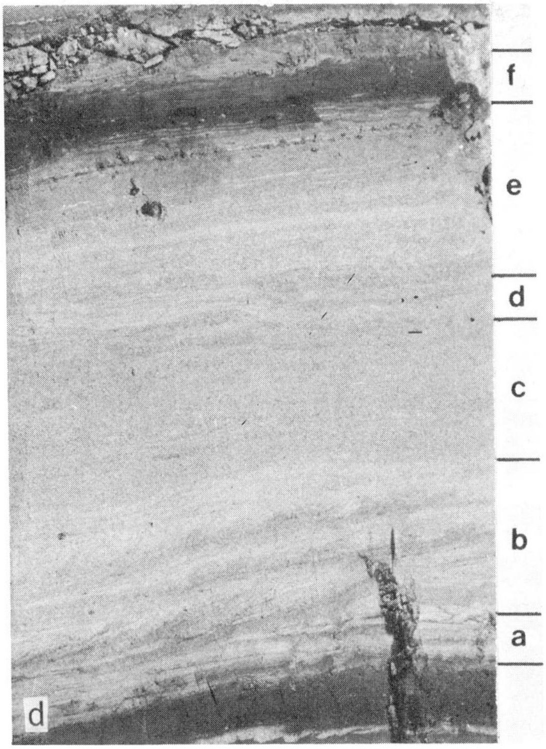

c
1cm

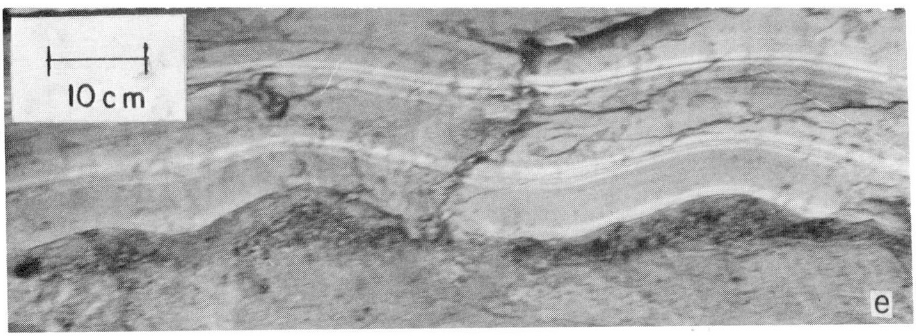




a) Vertical variation in the type of cross-lamination in thick sandy varves. (a) From ripple-drift lamination with full stoss-side erosion towards the bottom, the structure changes to sinusoidal ripples towards the top with increasing content of fine sediment. (b) Same sequence repeated and grading upward into clay (loc. 15).

b) Isolated ripples constituting the silt (summer) layers embedded in thick clay (winter) layers (loc. 18).



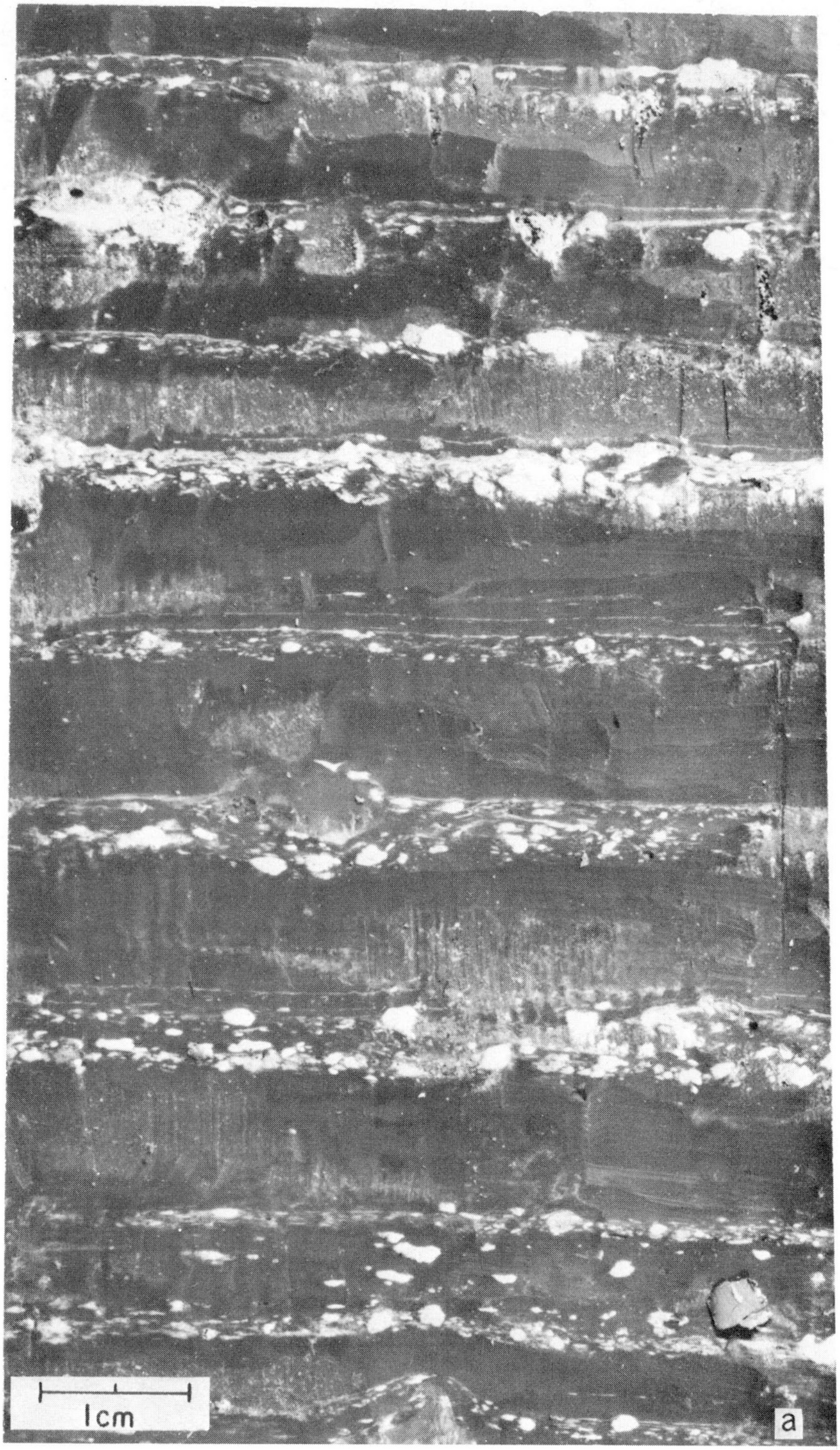


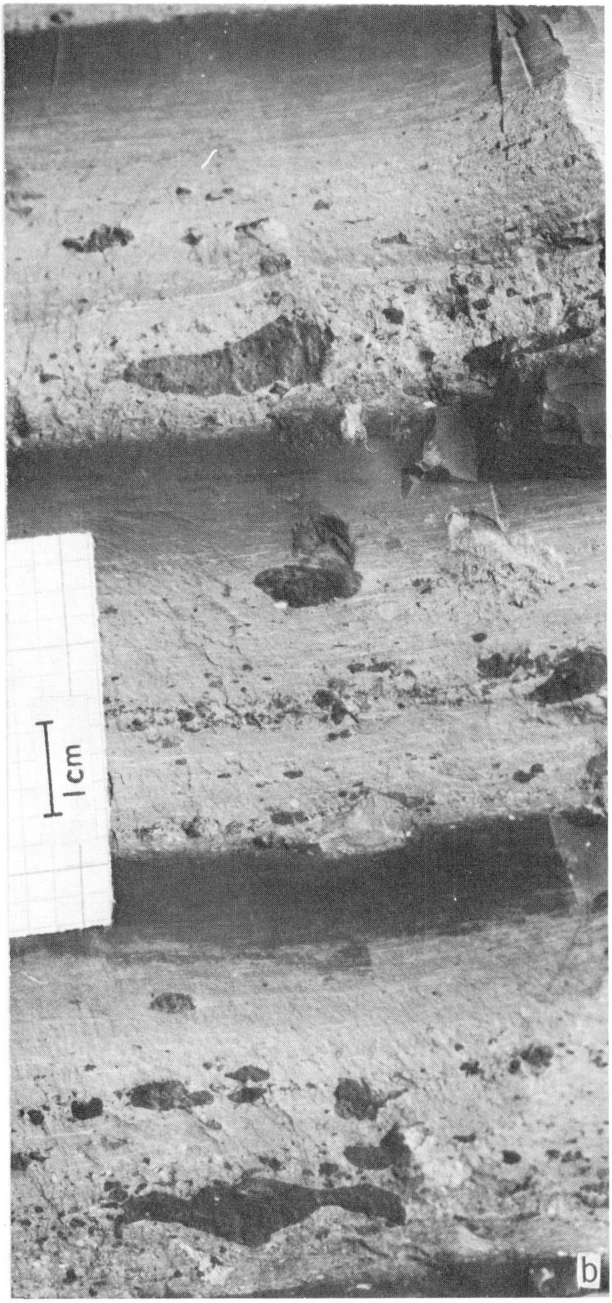
c) Vertical sequence of lamination: (a) graded bed, (b) parallel lamination and graded bed, (c) parallel lamination, (d) cross lamination (high-amplitude ripples), (e) parallel and cross-lamination (low amplitude ripples), and (f) parallel lamination grading into (g) clay towards the top (loc. 1).

d) Vertical sequence of laminations: (a) parallel, (b) cross, (c) parallel, (d) cross, (e) parallel, and (f) clay. Overall grading to clay (loc. 12).

e) Ripples in poorly sorted gravelly sand at the base of a varve series (loc. 12).

Plate 3. Cross-lamination in varves (sandy facies).

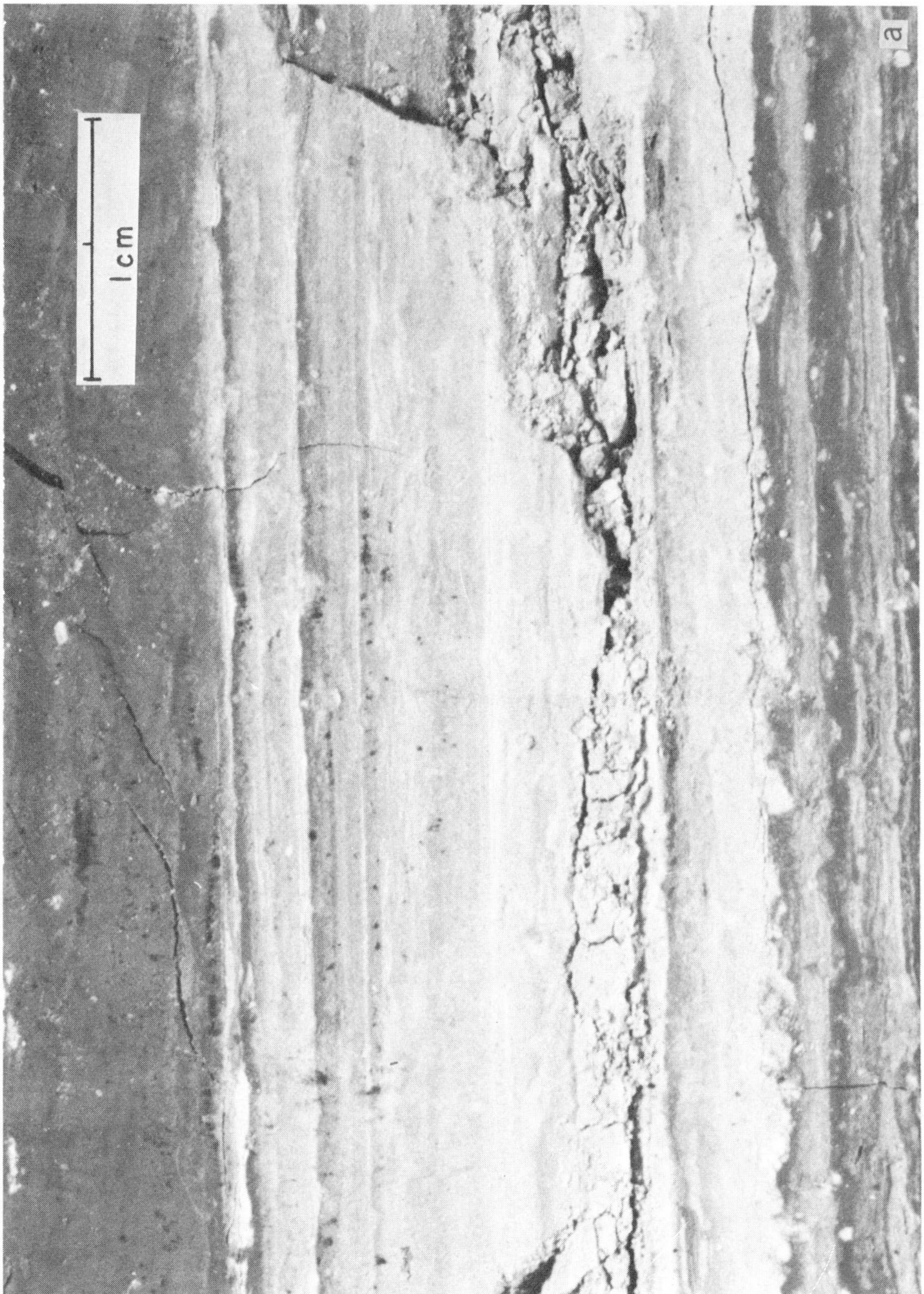

1cm
a

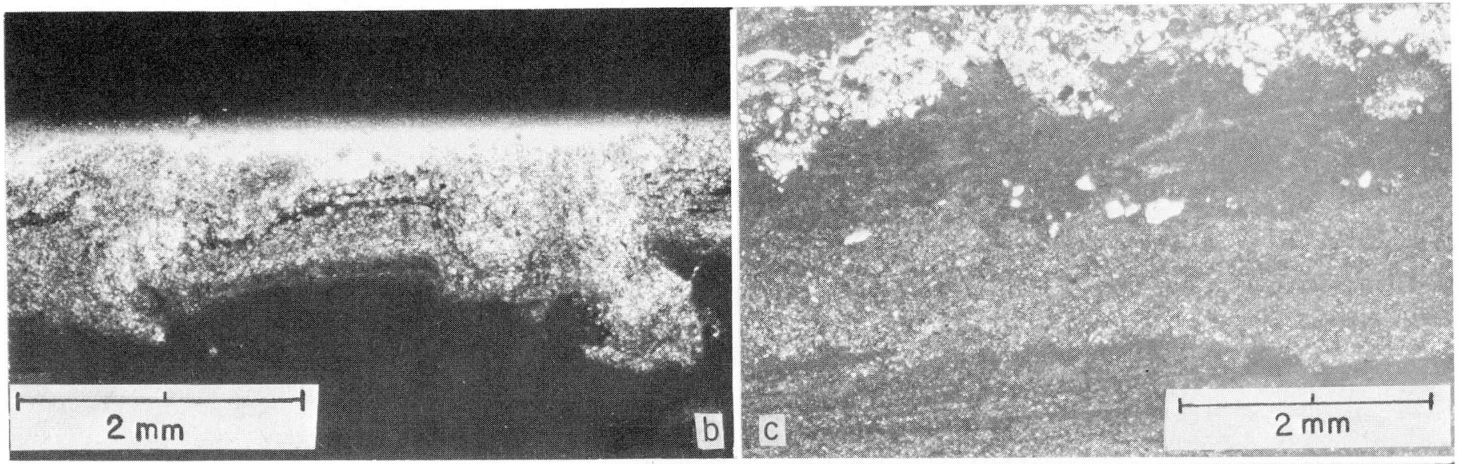


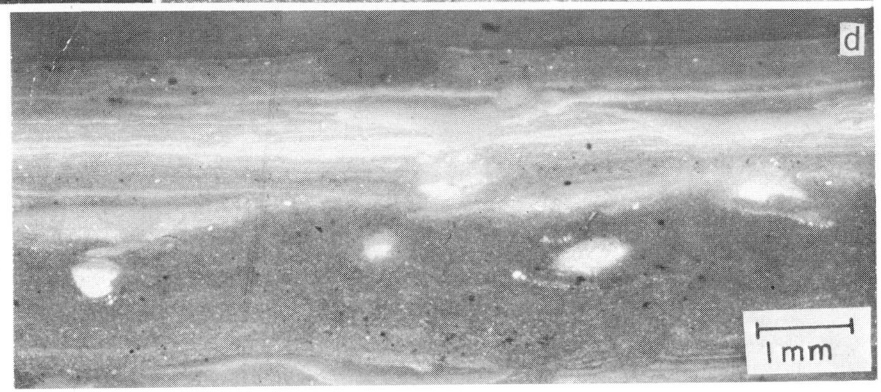
a) Diamictic varve (loc. 3). Summer layer entirely made up of broken fragments (clasts) of light coloured silt embedded in clay matrix. A few very thin, continuous silt layers and a few slump structures are present.

b) Diamictic varves from Don Valley, Toronto (loc. 19). Summer layer composed of silt or clay clasts embedded in silt matrix. Note grading and parallel lamination in the silt layers.

Plate 4. Diamictic varves.


1 cm
a
a

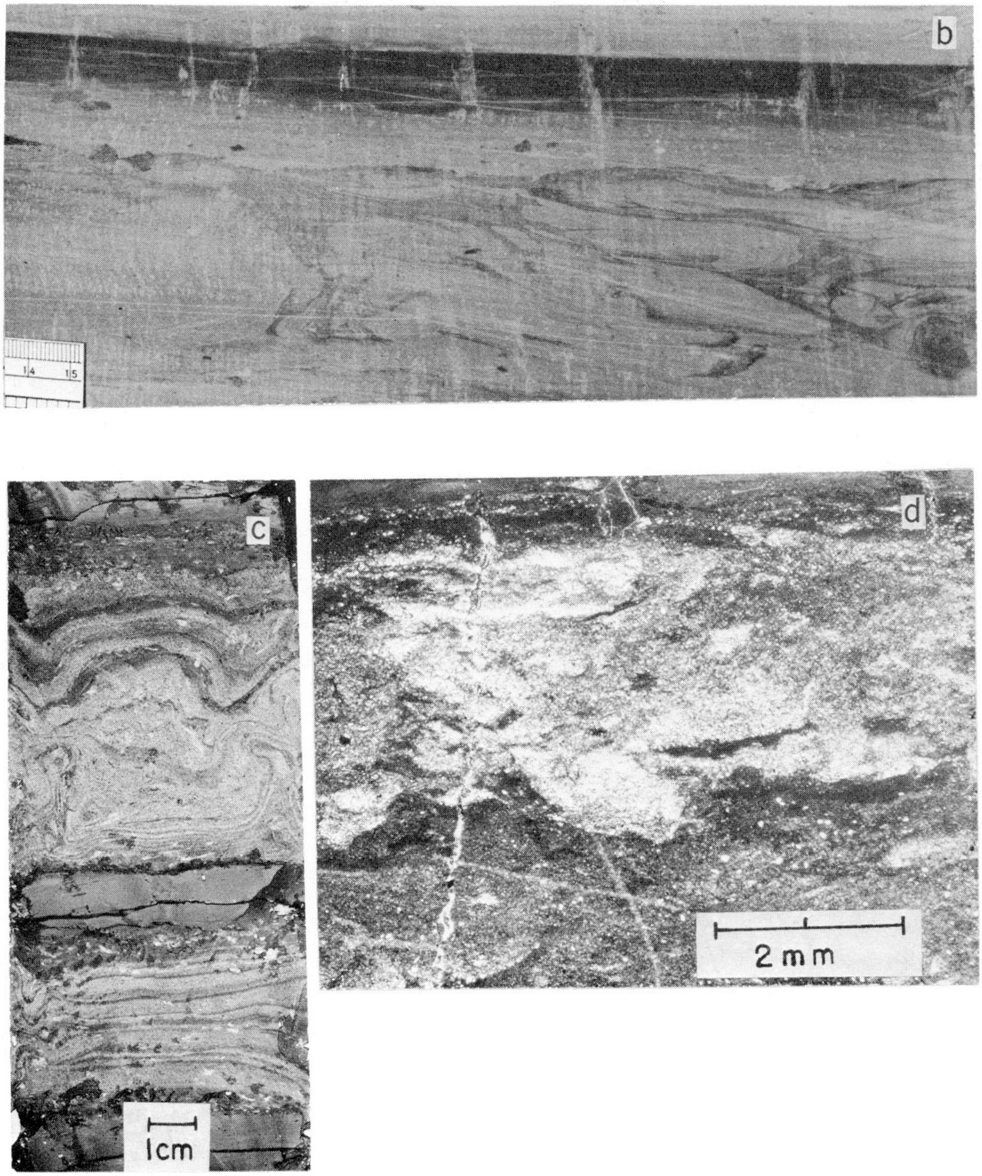




a) Load structure developed within multiple graded units. Unit (a), a graded bed with a loaded base, is a single turbidite sedimentation unit. Note loaded structures at the base of other graded units (loc. 2).
b) Details of load structures shown in photomicrograph of thin section. Note disrupted internal lamination within load structure (loc. 2).
c) Concentration of coarse grains (max. 0.25 mm) in load pockets in silty varves (loc. 15).
d) Microscopic channel (2 mm wide, 3/4 mm deep) showing truncation of laminae. Isolated silt lenses are possibly load structures connected in the third dimension (loc. 2).

Plate 5. Load and associated structures in varves (silty facies).


a
1 cm



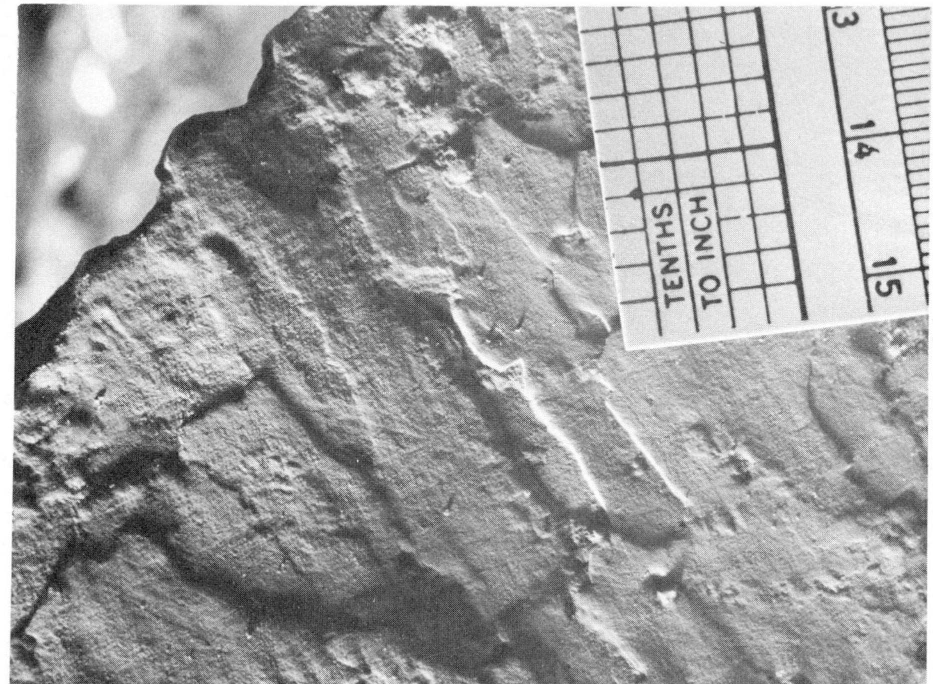
a) Slump structures in sandy varves, Rideau River, Ottawa (loc. 12). Slump movement right to left.

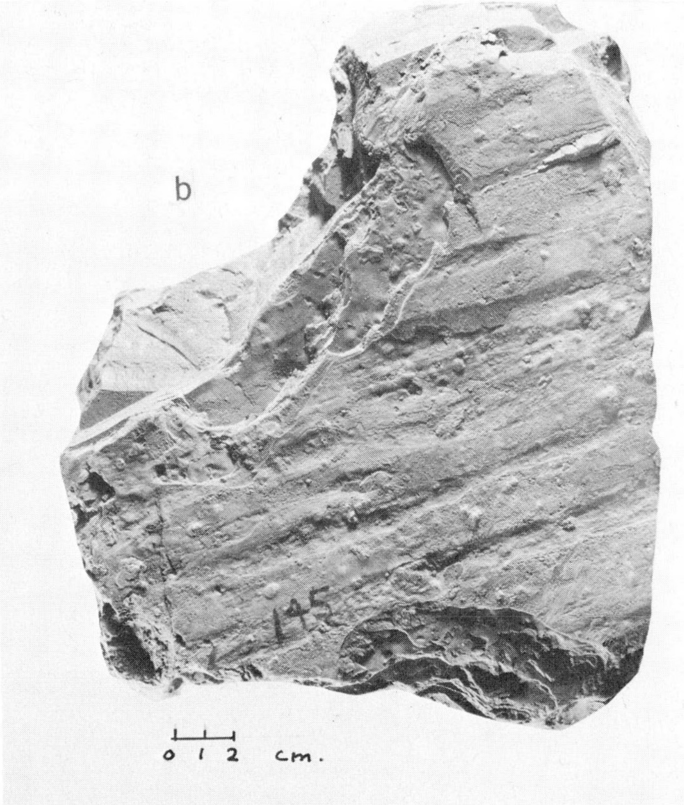
b) Slump structure in silty varve. The upper part, which is not affected by slumping, grades into clay above (loc. 19). Scale in cm.

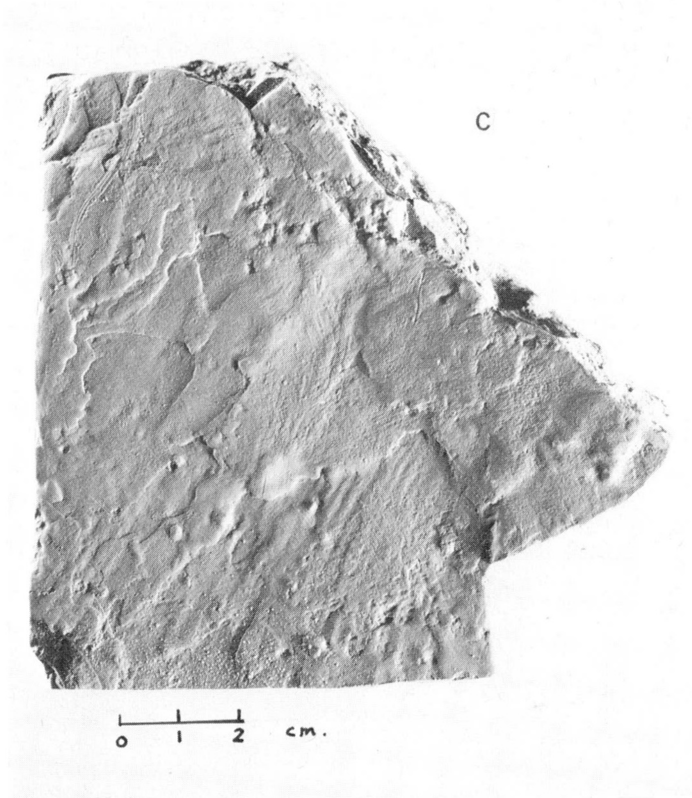
c) Contorted lamination in silty varves (loc. 3).

d) Photomicrograph of a very thin silt layer. Note flowage folds faintly delineated by thin white layers in the middle part (loc. 19).

Plate 6. Deformation structures in varves

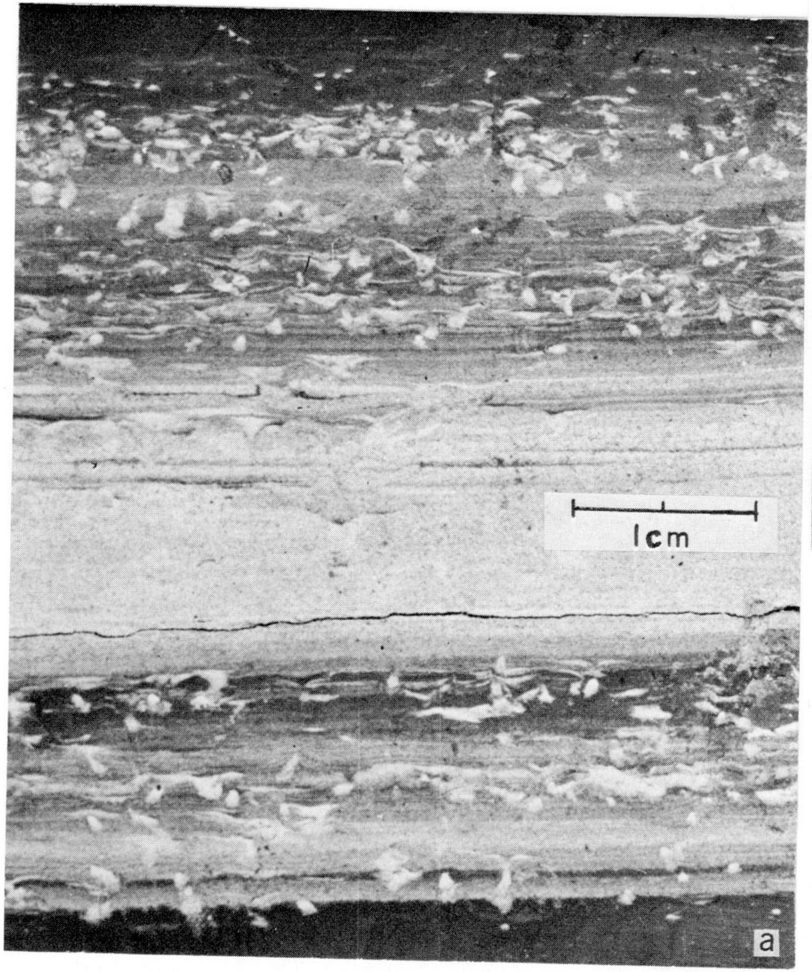

TENTHS
TO INCH
13
14
15
a

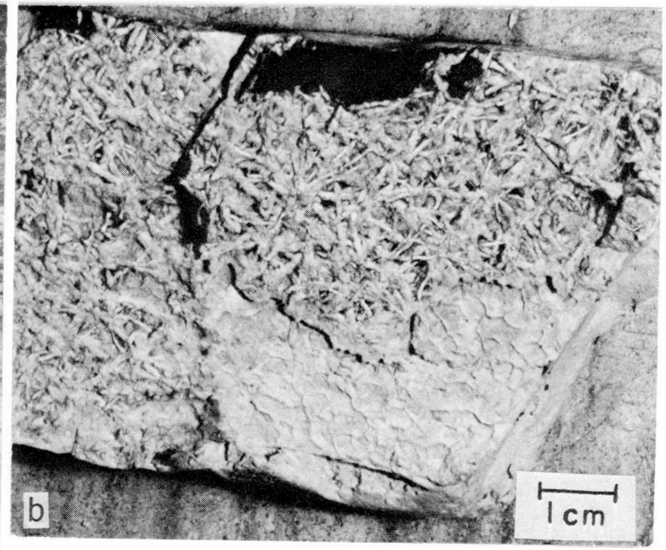




a) Parting lineation in the top surface of sandy varve. A very faint cross lineation is also visible.
b) Parallel linear depressions on bottom surface probably corresponding to "longitudinal ridges" (Dzulynski and Walton, 1965, p. 61) on bedding plane.
c) Parting lineation on top surface of bedding plane.

Plate 7. Current lineations on bedding planes in sandy varves (All examples from loc. 19. Note knobby pattern on bedding plane besides the lineation.

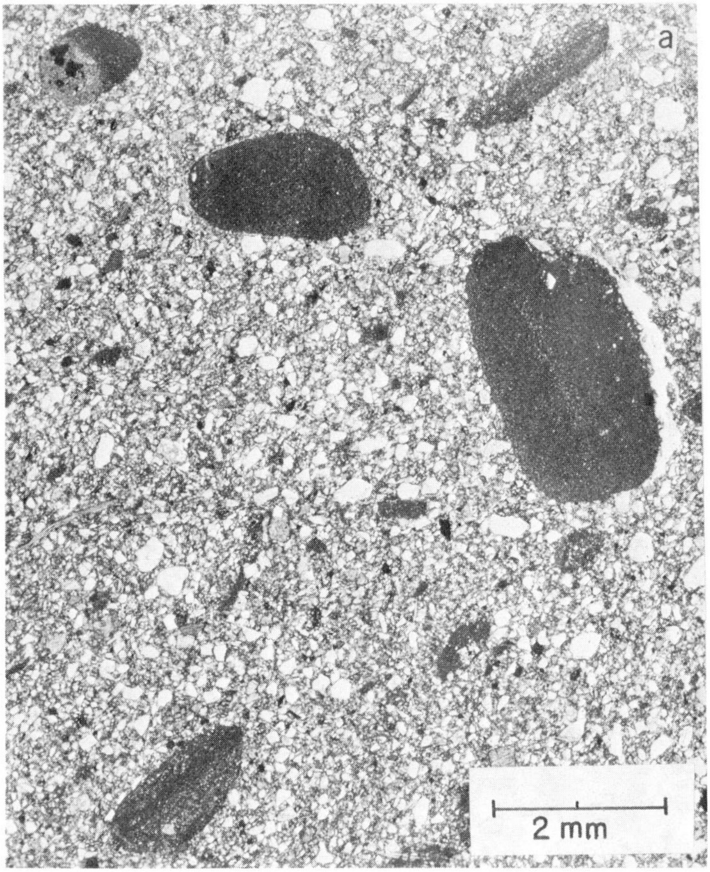




a) Burrows in section in sandy varves. They are confined to the silt layer both along and across bedding plane. Photograph of hand specimen from loc. 5.
b) Burrows in plan view: radiating and criss-cross, straight and curved ridges (type I) seen on the bottom surface of a bedding plane (loc. 5). Illustrations (a), (d), and (e) are cross-section views of type I.
c) Burrows in plan view on top of a bedding plane (loc. 19). At least two types are present here. Straight and continuous ridges (type II) and rows of small mounds (type III).
d) Photomicrograph of burrows seen in cross-section. Burrows cut across the bedding plane at all angles and destroy the planar structure (loc. 1).
e) Same as Illustration (d). Burrows (near the centre of the picture) and load structures producing disturbed bedding (loc. 2).

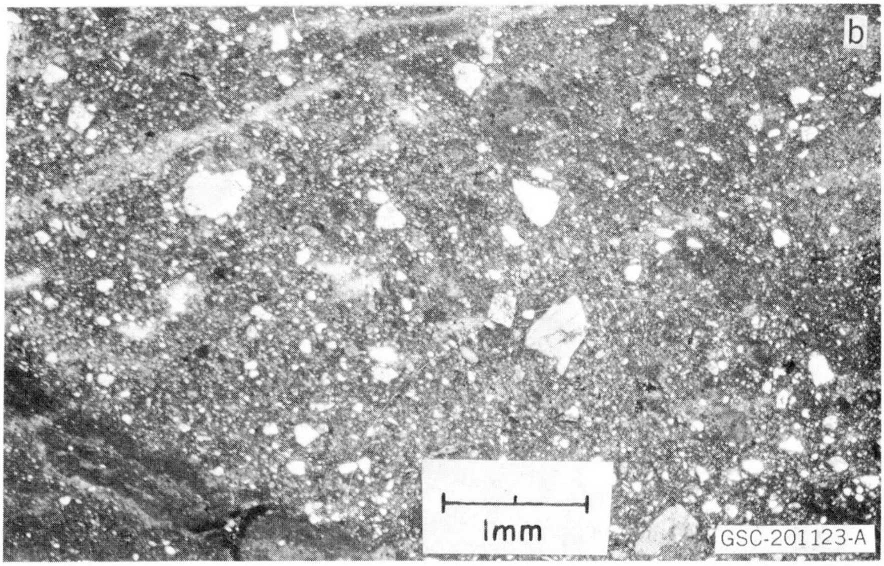
Plate 8. Trace fossils in the varves


c
3 cm
e
2 mm
d
4·5 mm



a) Rounded clasts of clay (dark grains) in the silt or summer layer of sandy varves. Note poor sorting of the assemblage. Light coloured grains of quartz, feldspar and carbonate (loc. 14).
b) Microbreccia texture of the diamictic varves. Bedding planes not visible at the scale of the photograph (loc. 3).
c) Diamictic varves showing clusters and lenses of coarser material embedded in clay. Bedding planes distinctly visible (loc. 19).

Plate 9. Texture of the varves


b
1mm
GSC-201123-A


c
2mm

REFERENCES

Agterberg, F.P., and Banerjee, I.
1969: Stochastic model for the deposition of varves in glacial Lake Barlow-Ojibway, Canada; Can. J. Earth Sci., v. 6, p. 625-652.

Antevs, E.
1925: Retreat of the last ice sheet in eastern Canada; Geol. Surv. Can. Mem. 146, 142 p.

1928: The last glaciation; Am. Geog. Soc., Res., Ser. no. 17, 292 p.

Banerjee, I.
1966: Turbidites in a glacial sequence; a study from the Talchir Formation, Raniganj Coalfield, India; J. Geol., v. 74, no. 5, pt. I, p. 593-606.

Bokman, J.
1953: Lithology and petrology of the Stanley and Jackfork Formations; J. Geol., v. 61, p. 152-170.

Bouma, A.H.
1962: Sedimentology of some flysch deposits; Elsevier Publishing Co., Amsterdam, 168 p.

Dean, W.E., Jr., and Anderson, R.Y.
1967: Correlation of turbidite strata in the Pennsylvanian Haymond Formation, Marathon region, Texas; J. Geol., v. 75, no. 1, p. 59-75.

Deane, R.E.
1961: Geology of lacustrine clays; Proc. 14th Canadian soil mechanics Conf. 1960, Tech. Mem. no. 69, p. 174-183.

De Geer, G.
1940: Geochronologia Suecica Principles; Kungl. Svenska Vetenskapsak Handl. ser. 3, v. 18, no. 6, 367 p.

Dzulynski, S., and Walton, E.K.
1965: Sedimentary features of flysch and greywackes; Elsevier Publishing Co., Amsterdam, 274 p.

Hughes, O.L.
1955: Surficial geology of Smooth Rock and Iroquois Falls map areas, Cochrane district, Ontario; unpubl. Ph.D. thesis, Univ. of Kansas, Lawrence, Kansas, 190 p.

1965: Surficial geology of part of the Cochrane district, Ontario, Canada; in International Studies on the Quaternary, Wright, H.E. and Frey, D.G., eds., Geol. Soc. Am. Special Paper 84, p. 535-565.

Jackson, T.A.
1965: Power-spectrum analysis of two "varved" argillites in the Huronian Cobalt series (Precambrian) of Canada; J. Sediment. Petrol., v. 35, p. 877-886.

Jopling, A.V.
1966: Some applications of theory and experiment to the study of bedding genesis; Sedimentology, v. 7, p. 71-102.

Jopling, A.V., and Walker, R.G.
1968: Morphology and origin of ripple-drift cross-lamination, with examples from the Pleistocene of Massachusetts; J. Sediment. Petrol., v. 38, p. 971-984.

Karrow, P.F.
1967: Pleistocene geology of the Scarborough area; Ont. Dept. Mines, Geol. Rept. 46, 108 p.

Kimura, T.
1966: Thickness distribution of sandstone beds and cyclic sedimentations in the turbidite sequences at two localities in Japan: Bull. Earthquake Res. Inst., Tokyo Univ., v. 44, no. 2, p. 561-607.

Kuenen, P.H.
1951: Mechanics of varve formation and the action of turbidity currents; Geol. Fören. Stockholm Förhandl., v. 73, p. 69-84.

1964: Deep-sea sands and ancient turbidites; in Turbidites, Bouma, A.H., and Brouwer, A., eds., Elsevier Publishing Co., Amsterdam, p. 3-33.

Lajtai, E.Z.
1967: The origin of some varves in Toronto, Canada; Can. J. Earth Sci., v. 4, p. 633-639.

Mathews, W.H.
1956: Physical limnology and sedimentation in a glacial lake; Geol. Soc. Am. Bull., v. 67, p. 537-552.

1963: Sediment transport from Athabasca glacier, Alberta; Publ. No. 65, Intern. Assoc. Sci. Hydrology, Land Erosion, Precipitation Hydrometry, Soil moisture, p. 155-163.

McBride, E.F.
1962: Flysch and associated beds of the Martinsburg Formation (Ordovician), Central Appalachians; J. Sediment. Petrol., v. 32, p. 39-91.

Nederlof, M.H.
1959: Structure and sedimentology of the Upper Carboniferous of the Upper Pisuerga Valleys, Cantabrian Mountains, Spain; Leidse Geol. Mededel., v. 24, p. 603-703.

Prest, V.K., Grant, D.R., and Rampton, V.N.
1968: Glacial map of Canada; Geol. Surv. Can.

Quigley, R.M.
1956: A study of the occurrences, properties and origins of varved clay; unpubl. M.Sc. thesis, Univ. of Toronto, Toronto, Ontario, 94 p.

Rees, A.I.
1966: Some flume experiments with a fine silt; Sedimentology, v. 6, no. 3, p. 209-240.

Schenk, P.E.
1965: Depositional environment of the Gowganda Formation (Precambrian) at the south end of Lake Timagami, Ontario; J. Sediment. Petrol., v. 35, p. 309-318.

Seilacher, A.
1962: Paleontological studies on turbidite sedimentation and erosion; J. Geol., v. 70, p. 227-234.

Unrug, R.
1959: On the sedimentation of the Lgota beds (Bielsko area, Western Carpathians): Ann. Soc. Géol. Pologne, v. 29 (2), p. 197-225.

1963: Istebna beds - a fluxoturbidite formation in the Carpathian flysch: Ann. Soc. Géol. Pologne, v. 33 (1), p. 49-92.

Vassoyevich, N.B., and Bezhayev, M.M.
1961: Trial correlation by varves of Upper Carboniferous flysch sections in the Urals; Doklady, Earth Sci. Sect., Akad. Nauk, SSSR: v. 149, p. 91-94.

Walton, E.K.
1967: The sequence of internal structures in turbidites; Scottish J. Geol., v. 3, pt. 2, p. 306-317.

Walker, R.G.
1967: Turbidite sedimentary structures and their relationship to proximal and distal depositional environments; J. Sediment. Petrol., v. 37, p. 25-43.

Watt, A.K.
1954: Correlation of the Pleistocene geology as seen in the subway with that of the Toronto region, Canada; Proc. Geol. Assoc. Can., v. 6, pt. II, p. 69-81.

PART B

NATURE OF THE GRAIN-SIZE DISTRIBUTION OF SOME PLEISTOCENE GLACIAL VARVES OF ONTARIO, CANADA

ABSTRACT

The nature of grain-size distributions was investigated in a suite of Pleistocene varves belonging to glacial Lake Barlow-Ojibway in northern Ontario and Lake Iroquois in southern Ontario. Separate size-analyses were made for 27 silt (summer) and 11 clay (winter) layers and they show significant differences. In silt layers, thickness is related to grain size and the number of modes in silt is never more than two. In clay layers, on the other hand, no relationship exists between thickness and grain size and the number of modes always exceeds two. This difference in size-characters between the silt and clay layers is believed to reflect their different origins, silt being deposited by turbidity current and clay from suspension and turbidity current.

Glaciofluvial sediments associated with varves were also analyzed and the results indicate that the whole range of glacial sediments from coarsest esker sand to finest varved clay can be classified into six characteristic populations. The total range of these populations can be compared to that of a typical till, a possible source material for all glacial sediments. It is suggested that random breakage by ice produces in tills a normal population which is differentiated into a number of mostly non-normal populations by subsequent sedimentary processes.

RÉSUMÉ

La nature de la répartition des grains a été étudiée dans une série de varves du Pléistocène du lac glaciaire Barlow-Ojibway au nord de l'Ontario et du lac Iroquois au sud de l'Ontario. On a fait des analyses granulométriques séparées de 27 couches de silt (été) et de 11 couches d'argile (hiver); ces analyses montrent des différences substantielles. Dans les couches de silt, il existe un lien entre l'épaisseur et la grosseur des grains, et il n'y a jamais plus de deux modes dans le silt. D'autre part, il n'y a pas de relation entre l'épaisseur et la grosseur des grains dans les couches d'argile et il y a toujours plus de deux modes. On croit que cette différence de caractère des grains entre les couches de silt et celles d'argile reflète leur origine différente: le silt ayont été déposé par des courants de turbidité et l'argile par suspension et par des courants de turbidité.

Les sédiments fluvio-glaciaires associés aux varves ont aussi été analysés et les résultats indiquent que toute la série des sédiments glaciaires, depuis le sable le plus grossier des eskers jusqu'à l'argile la plus fine des varves, peut être divisée en six populations caractéristiques. Toute la série de ces populations peut se comparer à celle d'un till typique qui est une source possible de matériau pour tous les sédiments glaciaires. On suggère que la fragmentation au hasard par la glace produit dans un till une population normale qui est différenciée en un nombre de populations surtout non-normales par les processus sédimentaires subséquents.

INTRODUCTION

Three major aspects of Pleistocene glacial varves in Ontario were studied in connection with a research project on varves. Results of the first two aspects of the study, namely, a stochastic model of the varve time-series and the stratigraphy and sedimentary structures of the varves have already been compiled and published (Agterberg and Banerjee, 1969 and companion paper, this report, Part A). The present paper deals with the third aspect of the study, interpretation of grain-size distributions in the varves in the light of their proposed model of sedimentation. The grain-size data of the varves as presented here have been examined in the light of a model of sedimentation inferred from previous extensive field and laboratory study of the stratigraphy and sedimentology of these varves. Only a brief mention of the proposed model has been made in the text of this paper and for a fuller discussion the reader should refer to Part A of this report.

Size distributions were investigated in 38 samples (27 silt + 11 clay layers) of varves belonging to glacial Lake Barlow-Ojibway in northern Ontario and Lake Iroquois in southern Ontario. Besides the varves, glaciofluvial sediments associated with them were sampled from two eskers and one kame delta. The location of the samples is shown on Figures 1 and 4 of the companion paper (Pt. A). Based on their grain-sizes and sedimentary structures, the varves under study have been grouped into the following three facies according to the properties of the silt (summer) layer: (1) sandy - coarse silt with cross, parallel or convolute laminae and graded bedding, (2) silty - fine silt with simple or multiple graded units and parallel laminae, (3) diamictic - fine silt in which sand-sized aggregates of coarse silt are embedded. Only the sandy and silty facies were analyzed for grain-size because the diamictic varves with their large content of silt clasts are unsuitable for disaggregation.

According to the model of sedimentation proposed here, the summer layer of the varve couplet was deposited by a turbidity current and the winter layer was formed by deposition out of suspension. The deposits of the turbidity current grade vertically from silt to clay. The most conspicuous plane of separation in the varve couplet, characterized by an abrupt change of colour, subdivides the varve into a silt (the so-called "summer") layer and a clay (the so-called "winter") layer. Genetically, the silt layer represents the coarser, basal portion of a turbidite whereas the clay layer represents material deposited mostly from suspension plus a small thickness of turbidite clay. Hence, neither the total silt nor the total clay layer is a pure sedimentation unit although both of them approach such a unit.

GRAIN-SIZE DATA

Sampling

In sampling varves for size analysis, the total silt and the total clay layers were sampled separately. The layers were scraped with a razor blade from tray samples of varves so that each silt layer and each clay layer is a clean sample. Where individual layers were too thin, three or four adjacent silt and clay layers were combined to make one whole sample.

The sampled silt layers show cross and parallel laminae and simple or multiple grading. Most layers are structurally homogeneous but a few multiple graded units are not homogeneous, consisting of several sedimentation units.

Grain-size analysis

All the samples were analyzed in the sedimentological laboratory of the Geological Survey of Canada in Ottawa. After disaggregation of the sample, sand was removed by wet sieving. The silt and clay portion was dispersed by boiling and by the addition of 100 ml of 0.5 N sodium hexametaphosphate to 900 ml of suspension. Pipette analysis was then used to determine grain-size distribution of the silt and clay fraction. Half phi intervals were chosen for the analyses. Most of the samples were analyzed up to 10 ϕ approximately 1 μ). In most cases such a procedure leaves an open-ended distribution which, in the case of clay layers, contains only 50-60 per cent of the total sizes present. Hence, in many cases (in all analyses which fall short of 90 per cent of the material present) interpolation of the rest of the cumulative curve has been done using Folk's (1968) technique. Cumulative curves were drawn on arithmetic probability paper using Krumbein's phi scale.

Size-parameters suggested by Folk and Ward (1957) were then calculated for the samples and frequency distributions of the parameters and their interrelationships were studied.

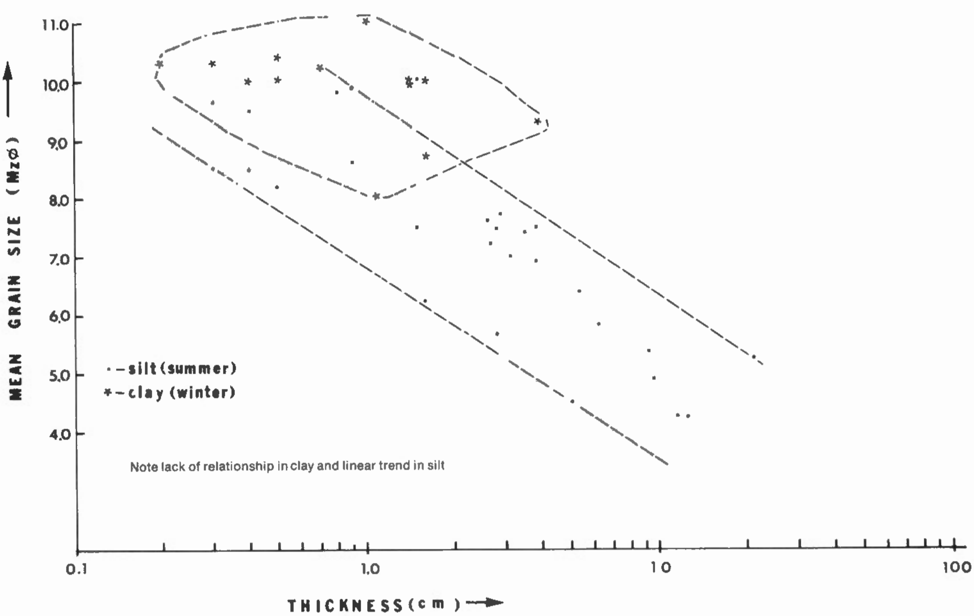


Figure 1. Plot of mean grain size against thickness of both silt (summer) and clay (winter) layers.

Results

Before discussing the nature of the grain-size distributions, the following two features of the varve couplets will be discussed:

1) Relation between grain-size and thickness of the varved layer,
2) Difference in the nature of grain-size distributions in the silt and clay layers.

Thickness vs. mean size:

Figure 1 is a plot of mean grain-size (Mz or Graphic Mean) of the silt and clay layers against their thickness. It is evident from the diagram that the mean size of the silt layers is related to the thickness whereas in clay layers no such relationship exists. Similarly, when the patterns of thickness variation in silt layers are compared with their patterns of grain-size variation, there is a marked correspondence (Fig. 2). No correspondence is present in the case of clay layers.

From extensive field study of the varves made earlier, it has been suggested that the silt layer represents deposits made by turbidity currents and the clay layer mostly represents deposits made from suspension in still water. If this model of sedimentation is assumed for the varve couplets, an explanation for the above-mentioned relationship between thickness and mean size may be offered. In the case of silt, the mean size depends partly on the velocity of the turbidity current, which depends on the effective density of the currents and, in turn, on the total load. The total load also controls the thickness of the layer. Hence, thickness and mean size are related in the silt layer. As no such process controls the thickness of the clay layer, it is independent of grain-size.

Differences in the nature of grain-size distributions in the silt and clay layers:

General: When grain-size distributions are compared (Table I) it is found that, on the average, clay layers are finer than the corresponding silt layers by about 2 ϕ and are more poorly sorted, less skewed and polymodal in nature.

Modality: Silt shows a unimodal distribution because it is hydrodynamically homogeneous representing the uniform load of the turbidity current. Clay layers, on the other hand, show typically polymodal distributions (Fig. 3) because clay is polygenetic. Probably, one of the modes represents the turbidite clay while the other modes represent heterogeneity of the source material.

Sorting: Because of the mixing of several modes mentioned above, the clay shows poorer sorting.

Skewness: All silt populations are strongly positively skewed. The long fine tail represents the suspension load of the turbidity current. It is equivalent to the matrix of the graded greywackes (Kuenen, 1966). Why the sediment in the clay layers has a less skewed distribution is not known. Perhaps this feature of the clay is irrelevant because it only depends on the proportions of mixing of several modes.

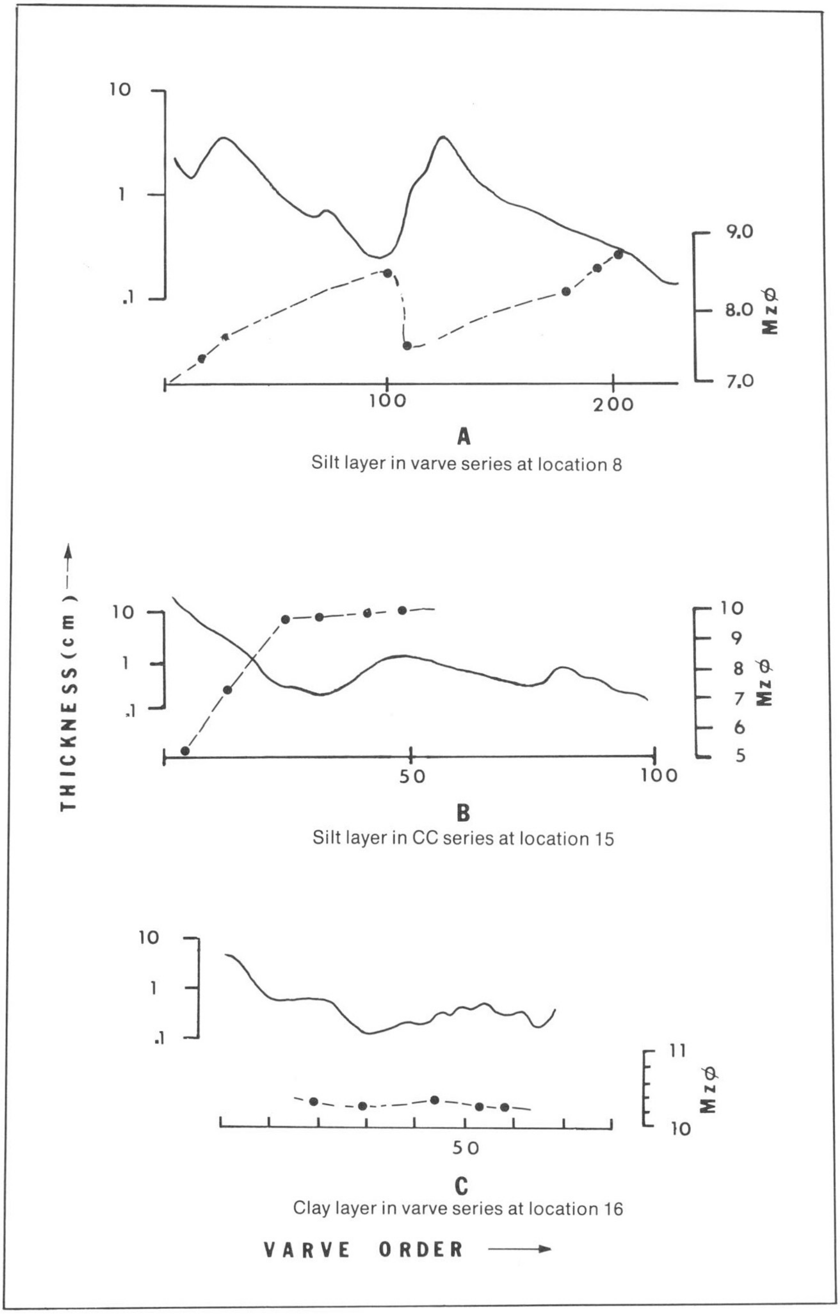


Figure 2. Comparison of patterns of variation in (1) varve thickness and (2) mean size (Mz) in different varve series.

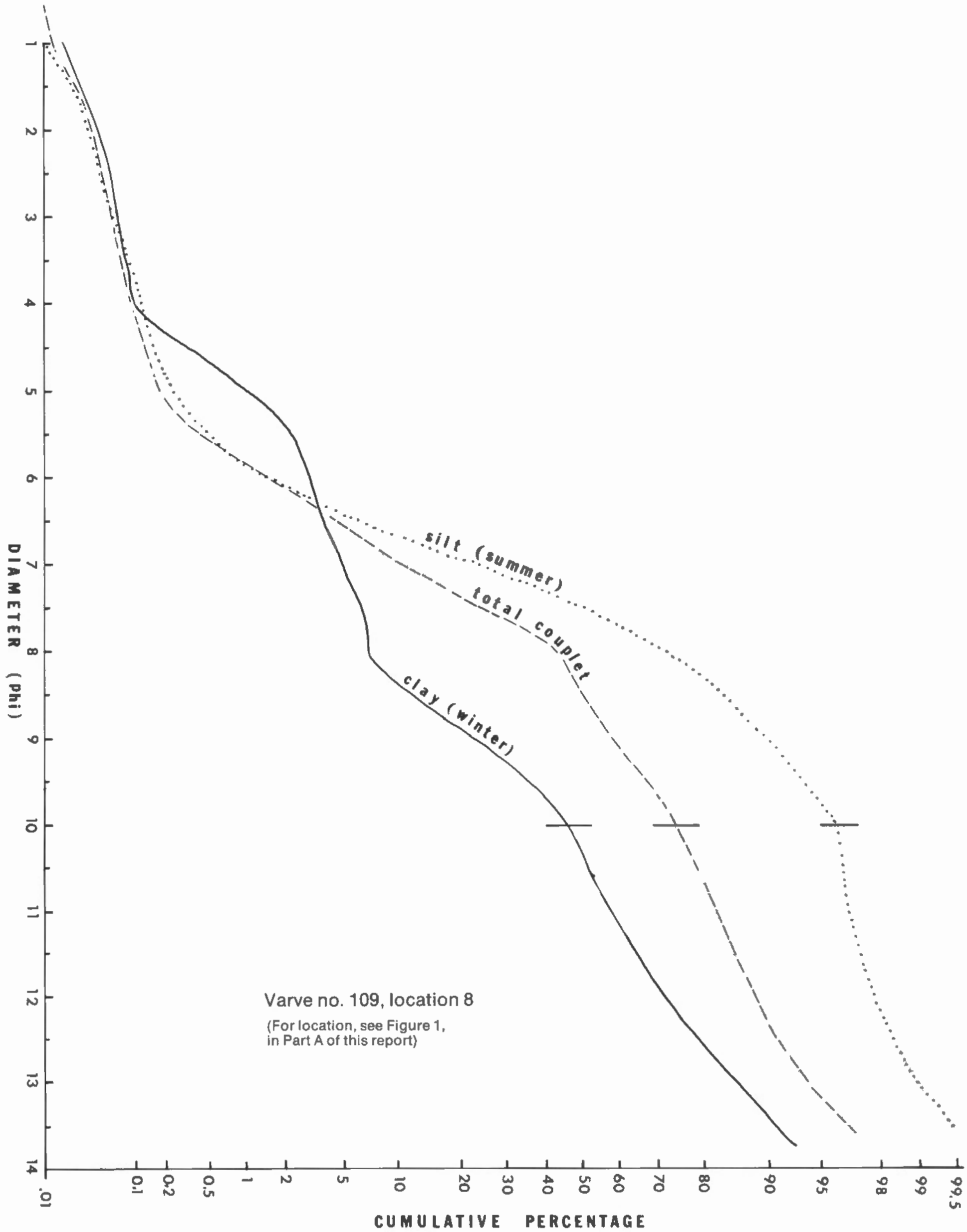


Figure 3. Cumulative curves showing the difference between silt and clay layers in the same varve couplet.

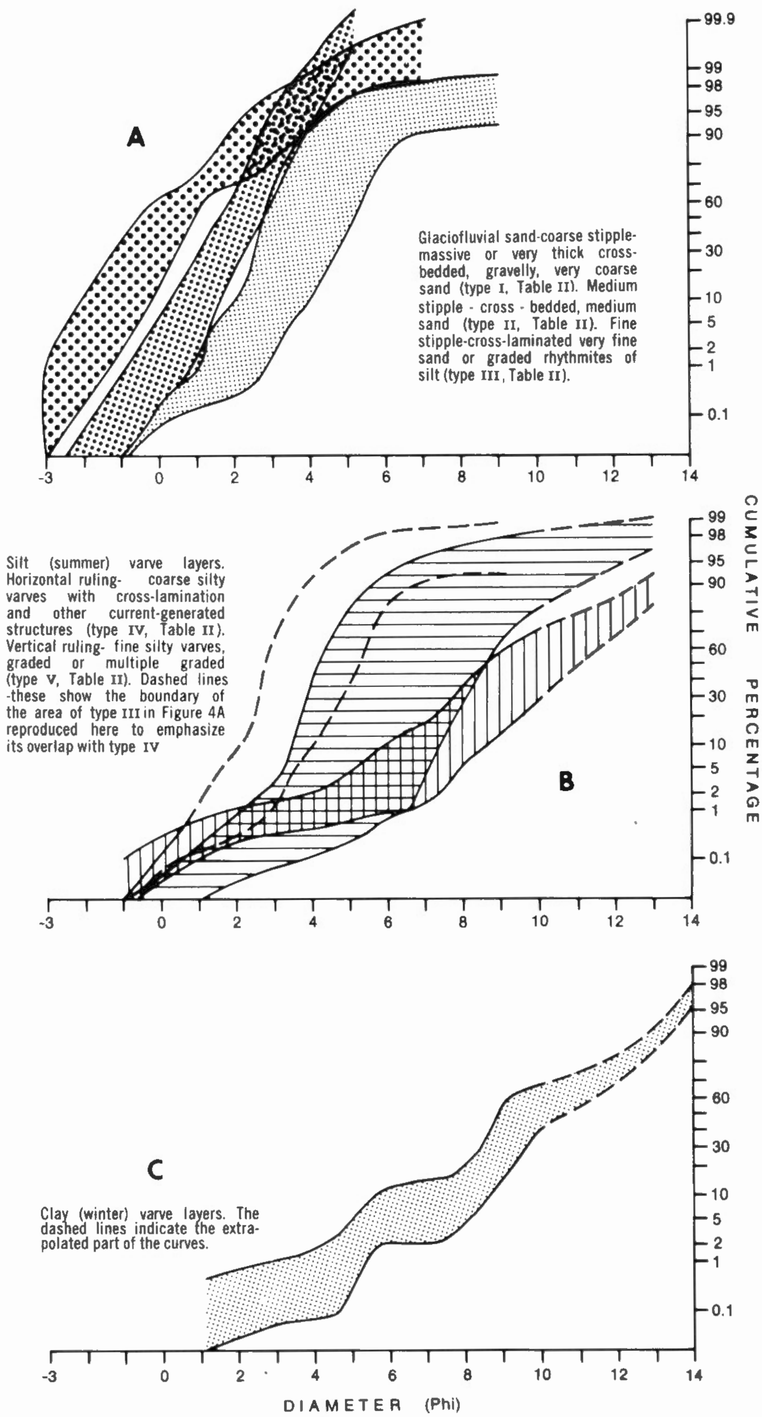


Figure 4. Types of size-distributions in glaciofluvial and glaciolacustrine sediments. The different patterns show distinctive areas **delineated** by all cumulative curves of a particular sediment type.

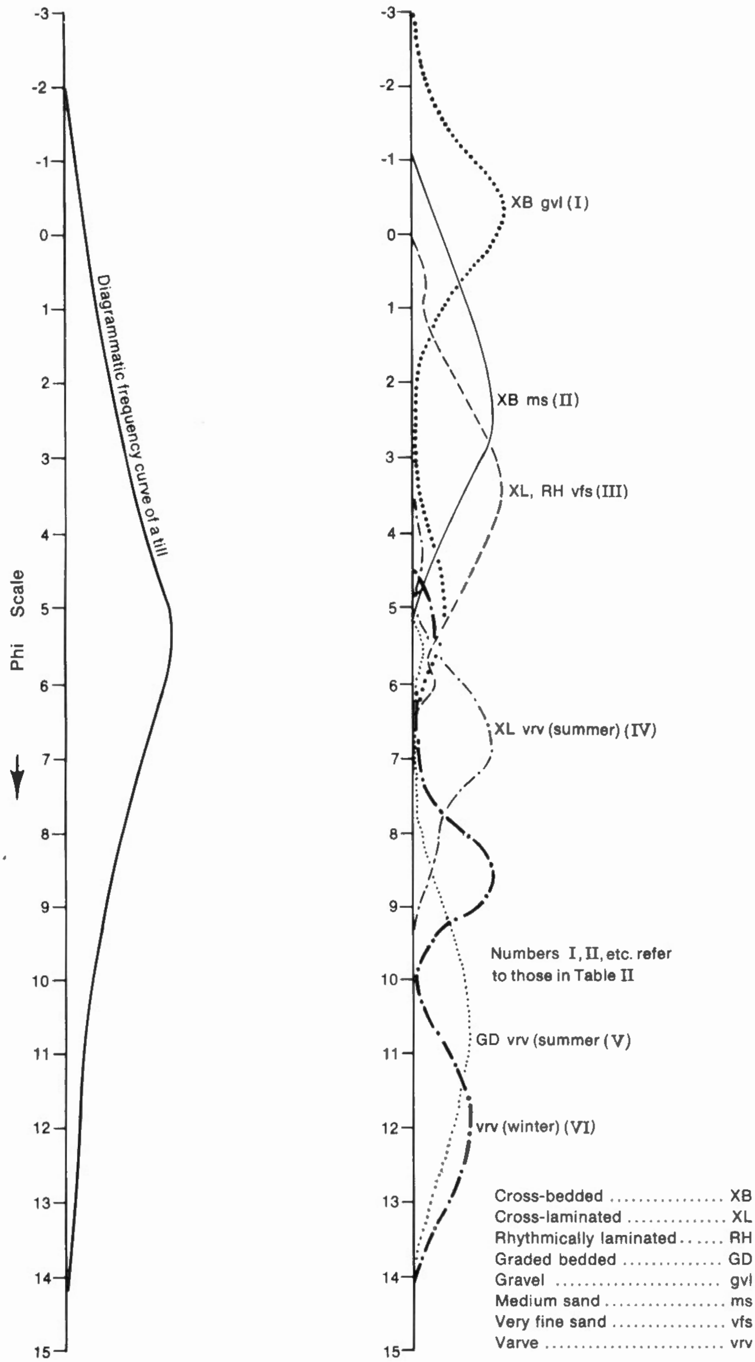


Figure 5. Diagrammatic sketch of the different frequency curves characterizing the populations described in Table I.

Types of Distribution

The results of the size-analyses were plotted on arithmetic probability paper using Krumbein's phi scale as abscissa. Most of the plots were non-linear and they have been grouped into several types based on the shape of the resulting curves. As a convenient way of showing the broad features of the cumulative curves, the area occupied by a group of curves is shown as a shaded zone in Figure 4A. The shape and position of the shaded zone typify each particular group.

Cumulative curves of silt and clay layers of varves can be classified into three groups. Each of the groups falls into distinct fields and have characteristic shapes (Figs. 4B and 4C). The varves represent the end member of a continuous series of sediments from glaciofluvial gravel and sand at one end, to glaciolacustrine silt and clay at the other. To complete the series, cumulative curves of the glaciofluvial sediments from eskers and kame deltas were also plotted (Fig. 4A). The whole series consists of six distinct groups each having a characteristic grain-size distribution (Table II). Except for type II, all the other distributions are non-normal.

For better visual appreciation of the different size distributions, a series of frequency curves characterizing each distribution has been drawn diagrammatically in Figure 5. It shows the entire range of the glacial sediments differentiated into at least six populations. Alongside these curves is shown a frequency curve drawn diagrammatically but based on actual size-analysis of a typical till. Unfortunately, the till sample used in the illustration comes from a different area as no size-analysis of till was available from the study area.

A comparison of the curves of the glaciolacustrine and glaciofluvial sediments with that of the till is revealing. The till, having a long range covering the combined range of all six populations mentioned above, shows a normal distribution. In contrast, the other sediments, which were in all probability derived from a till acting as a source sediment, have mostly non-normal distributions. It seems, therefore, that random breakage phenomenon produces a normal population in the till which, through subsequent differentiation by fluvial processes, is split up into several non-normal populations.

Interrelationship of size-parameters:

Interrelationship of mean size (Mz) and other size parameters (σ_1, Sk and Kg) is shown in Figure 6, parts A, C and D. To illustrate the size-sorting relationship in varves the data on grain-size distribution of glacial varves found in the works of Wallace (1927), Hansen (1940) and Quigley (1956) have also been used. The data have been summarized in Figure 6B, where medians of the sediments are plotted against Trask's sorting coefficient*. Comparison of these data with the results of the present investigation reveal similar relationships. The following points are of interest:

1) About half the silt (summer) layers of the varves plot as a distinct band with best sorting value near 4 ϕ (Fig. 6A). The data of previous workers also show a similar band although the best sorting value in that case lies near 6 ϕ (see Fig. 6B).

---

*Trask's sorting coefficient is defined as $\sqrt{Q_3/Q_1}$ where Q_3 is the 75 percentile and Q_1 the 25 percentile read from the cumulative curve.

2) Clay (winter) layers of the varves and finer silt layers plot in another band with a reverse size-sorting relationship (Fig. 6A). The same phenomenon is observed in Figure 6B.
3) Many graded, locally cross-laminated, and rhythmically laminated very fine sand and silt (turbidites) in eskers also plot within the band of silt layers of varves. This is consistent with the hypotheses that these two types of sediments are genetically related and that the rhythmites in eskers are proximal equivalents of the varves (see Part A).

   Another feature of this plot is that all samples of series PR (Fig. 6A) fall in a restricted zone and reveal a trend parallel to but separate from the general trend of the rest of the data. The reason for this is still unexplained because, in all other aspects the varves of this series behave in the same manner as the others.

Both the Mz vs. Sk (Fig. 6C) and Mz vs. Kg (Fig. 6D) diagrams reveal inverted V-shaped trends. In both diagrams values of Sk = 0 and Kg = 1, typifying a normal population, occur at two values of Mz, approximately at 2 ϕ and 10.5 ϕ. It has been mentioned earlier that the type II sediment (see Table II) is the only group with a normal population. The average Mz of this group is around 2 ϕ, which explains the occurrences of Sk = 0 and Kg = 1 values at this point. The second occurrence of these values at Mz = 10.5 ϕ is near the principal mode of population V. Although this population is non-normal, due to the dominance of the principal mode (containing about 80 per cent of the total sizes, see Table II) population V has a nearly symmetrical and mesokurtic distribution. From the above discussion it follows that normal population occurs in type II sediment which is a cross-bedded medium sand produced by fluvial processes in the lower flow regime. A nearly normal population occurs in type V sediment which is a graded silt layer of varves believed to be deposited by a turbidity current without bed load. It may be suggested that the reason why type V population departs from a normal distribution is the presence of multiple graded units in the samples. It is expected that in samples with single graded units the population would be normal.

TABLE I

Comparison of size-parameters of silt (summer) and clay (winter) layers in a single couplet.

Series	Varve no.	Layer	Mz	σ_1	Sk	Kg
NR	16	SILT	7.66	1.98	+0.36	1.52
		CLAY	9.50	2.72	+0.16	1.42
PR	18	SILT	7.52	0.97	+0.23	1.32
		CLAY	8.32	1.63	+0.34	1.33
PR	100	SILT	8.69	1.42	+0.29	1.83
		CLAY	10.76	1.83	+0.17	0.79
PR	109	SILT	7.60	0.91	+0.27	1.24
		CLAY	10.60	2.08	+0.14	0.93

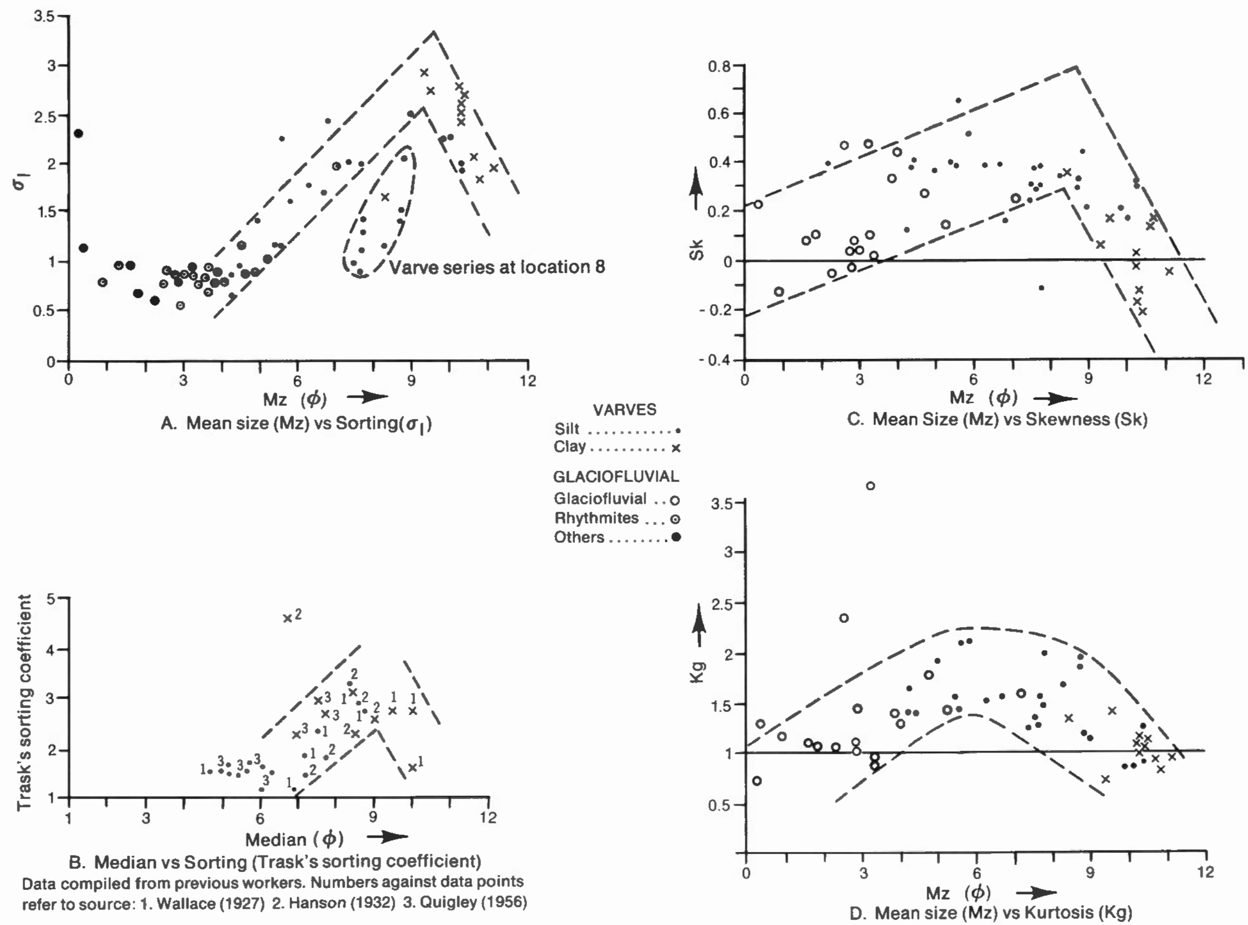


Figure 6. Interrelationship of different varve size-parameters.

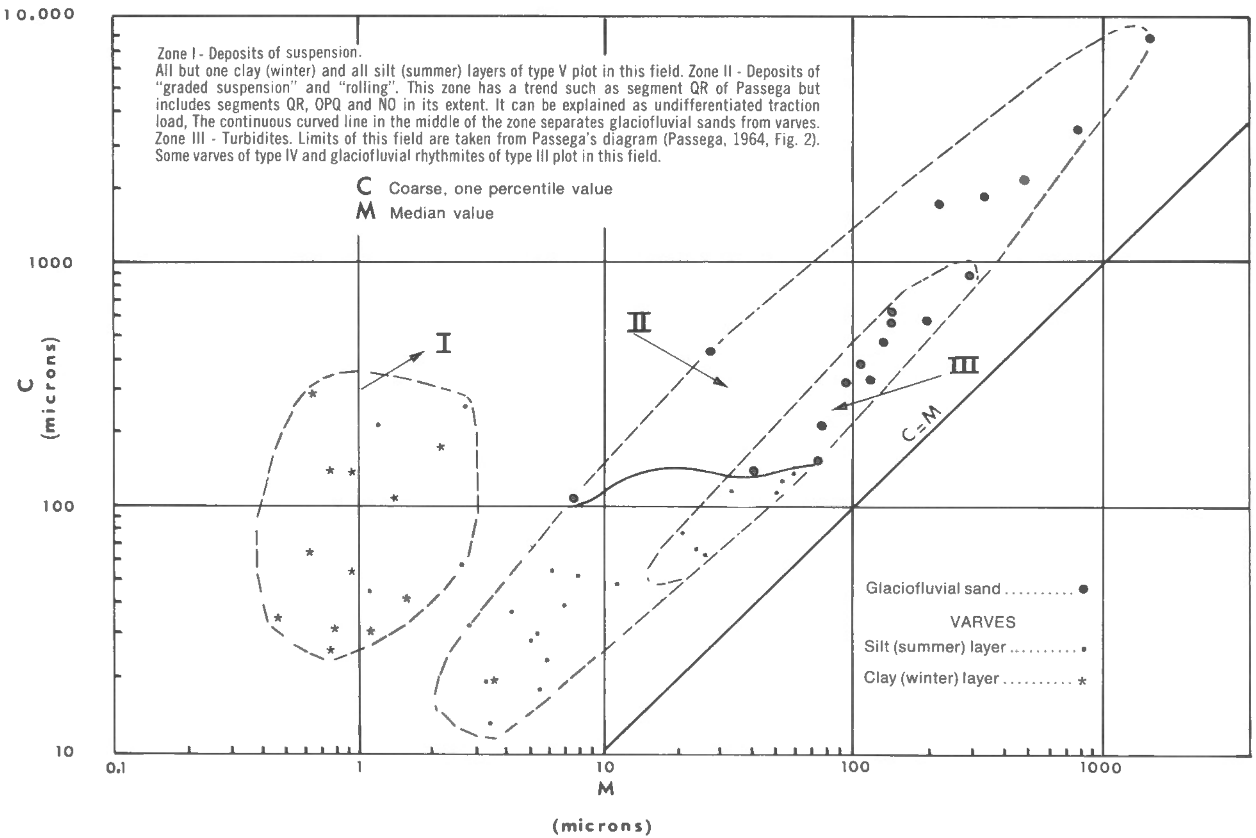


Figure 7. CM diagrams of glaciofluvial and glaciolacustrine sediments.

TABLE II

Size character of different sediment types

Type	Facies	Depositional Mechanism	Character of size-distribution
I	Massive or very thick cross-bedded, gravelly, very coarse sand	Normal tractive current, upper flow regime (?)	Bimodal, flattening at both ends. 2 populations: (i) 3 ϕ to 2ϕ 70-90% (ii) 3 ϕ to 7ϕ 10-30%
II	Cross-bedded medium sand and cross-laminated fine sand	Normal tractive current, lower flow regime	Unimodal, near normal - 1 ϕ to 5ϕ
III	Cross-laminated or graded rhythmite, very fine sand or silt	Turbidity current with bedload	S-shaped, flattening at both ends. Middle straight part - 1 ϕ to 6 ϕ, 90%
IV	Silt (summer) layer of varve. Cross or parallel laminated, simple or multiple graded	Turbidity current with bedload	S-shaped, flattening at both ends. Middle straight part - 5 ϕ to 8ϕ, 80%
V	Silt (summer) layer of varve. Simple or multiple graded	Turbidity current without bedload	2 line segments. Inflection at 5 ϕ to 7ϕ. Upper straight part 80%
VI	Clay (winter) layer of varve	Suspension	Polymodal 3 populations (i) 4.5 ϕ to 6ϕ (ii) 7.5 ϕ to 9ϕ (iii) 10ϕ to 14ϕ

<u>CM-plot</u>: Passega's CM diagrams (Passega, 1964) where one percentile grain-size (C) is plotted against median (M) can be helpful in the interpretation of depositional mechanisms. The CM plot of 55 samples under study (Fig. 7) show that the points fall in the following two groups: (1) all data on silt layers of varves and those from the glaciofluvial sediments delineate a linear band (II) parallel to the line C=M, (2) the clay layers of varves and silt layers of type V varves fall in a circular zone (I) which indicates absence of correlation between C and M values. The linear band corresponds to the QR segment of Passega's master CM diagram (Fig. 1, Passega, 1964). This segment, according to Passega, indicates loads of the "graded suspension"

zone. In Passega's diagram the upper limit of the zone (or Cs in his terminology, meaning the largest grain diameter than can be carried in graded suspension) is 390 μ. But in the present suite of samples, zone II continues without change of shape up to 10,000 μ. Hence, this zone not only represents the QR segment of Passega's diagram, but also includes segments OPQ and NO which, according to him, represent sediments transported by rolling. Therefore, zone II can be interpreted as the undifferentiated traction load. Zone III, in which plots of turbidites fall in Passega's diagram, is also shown in Figure 7. A number of data points of silt layers in varves fall in this zone. Some glaciofluvial sands, mostly very fine sand and silt believed to be turbidites, also plot in the same field. These turbidites are believed to be proximal equivalents of varves and are genetically related to them (see p. 7).

The occurrence of data points of fine silt layers of varves (type V population) in the same field of suspension as the clays indicates that, either they were also deposited straight out of suspension like the clay or they were deposited from turbidity current without a bed load (autosuspension currents). The latter suggestion is favoured because a genetic difference between the silt and clay layers is suggested even in these varves.

CONCLUSIONS

From this study of 38 (11 clay and 27 silt layers) size analyses of Pleistocene glacial varves in Ontario, Canada, a number of generalizations regarding the grain-size distribution of varves can be made.

1) Size characteristics of clay and silt layers in a varve couplet differ in a number of ways. Their differences can be explained by genetic differences inferred from sedimentary structures, namely the silt layer being deposited by turbidity currents and the clay layer being deposited largely out of suspension.
2) Silt layers fall into two categories (types IV and V). According to their size-character, these two types have been interpreted as being deposited by:
   i) turbidity currents with bedload
   ii) turbidity currents without bedload.
3) Size distributions of the continuous spectrum of sediments from esker gravel to varved clay have been studied. The presence of at least 6 populations, most of them markedly non-normal, is indicated. The only normal population is shown by cross-bedded medium sand of glaciofluvial origin. It is postulated that the probable source-material, a till, had a normal distribution with a long range which has been subsequently differentiated by sedimentary processes into six different size distributions of which only one is normal and the rest are non-normal.

ACKNOWLEDGMENTS

This work has been carried out under the constant help and guidance of Dr. John G. Fyles, Chief of the Terrain Sciences Division, Geological Survey of Canada. Thanks are due to Mr. Rolf Kihl and Mr. Ronald Kelly of the Sedimentology Laboratory of this Division, who have carried out the size analyses with great devotion and care. Dr. B.C. McDonald critically read the manuscript and offered many valuable suggestions.

REFERENCES

Agterberg, F.P., and Banerjee, I.
1969: Stochastic model for the deposition of varves in glacial Lake Barlow-Ojibway, Ontario, Canada; Can. J. Earth Sci., v. 6, no. 4, p. 625-652.

Folk, R.L.
1968: Petrology of sedimentary rocks; 2nd ed., Hemphill's, Austin, Texas, 170 p.

Folk, R.L., and Ward, W.C.
1957: Brazos river bar: A study in the significance of grain size parameters; J. Sediment. Petrol., v. 27, no. 1, p. 3-26.

Hanson, G.
1932: Varved clays of Tide Lake, British Columbia; Proc. Trans. Roy. Soc. Can., 3rd ser., v. 26, sec. 4, p. 335-339.

Kuenen, Ph. H.
1966: Matrix of turbidites: experimental approach; Sedimentology, v. 7, no. 4, p. 267-297.

Passega, R.
1964: Grain size representation by CM patterns as a geological tool; J. Sediment. Petrol., v. 34, no. 4, p. 830-847.

Quigley, R.M.
1956: A study of the occurrences, properties and origins of varved clay; unpublished M. Sc. thesis, Univ. of Toronto, Toronto, Ontario, 94 p.

Wallace, R.C.
1927: Varve materials and banded rocks; Proc. Trans. Roy. Soc. Can., v. 21, sec. IV, p. 109-118.

Geological Survey of Canada

Bulletins present the results of detailed scientific studies on geological or related subjects. Some recent titles are listed below (Information Canada No. in brackets):

193 Petrology and structure of Poplar Creek map-area, British Columbia, *by* Peter B. Read, $4.00 (M42-193)

194 Triassic petrology of Athabasca-Smoky River region, Alberta, *by* D. W. Gibson, $2.00 (M42-194)

195 Petrology and structure of Thor-Odin gneiss dome, Shuswap metamorphic complex, B. C., *by* J. E. Reesor and J. M. Moore, Jr., $2.50 (M42-195)

196 Glacial geomorphology and Pleistocene history of central British Columbia, *by* H. W. Tipper, $4.00 (M42-196)

197 Contributions to Canadian paleontology, *by* B. S. Norford, *et al.*, $6.00 (M42-197)

198 Geology and petrology of the Manicouagan resurgent caldera, Quebec, *by* K. L. Currie, $3.00 (M42-198)

199 The geology of the Loughborough Lake region, Ontario, with special emphasis on the origin of the granitoid rocks—A contribution to the syenite problem (31 C/7, C/8), *by* K. L. Currie and I. F. Ermanovics, $3.00 (M42-199)

200 Part I: Biostratigraphy of some Early Middle Silurian Ostracoda, eastern Canada; Part II: Additional Silurian Arthropoda from arctic and eastern Canada, *by* M. J. Copeland, $1.50 (M42-200)

201 Archaeocyatha from the Mackenzie and Cassiar Mountains, Northwest Territories, *by* R. C. Handfield, $2.00 (M42-201)

202 Faunas of the Ordovician Red River Formation, Manitoba, *by* D. C. McGregor, *et al.*, $2.00 (M42-202)

203 Geology of lower Paleozoic formations, Hazen Plateau and southern Grant Land Mountains, Ellesmere Island, *by* H. P. Trettin, $3.00 (M42-203)

204 Brachiopods of the Detroit River Group (Devonian) from southwestern Ontario and adjacent areas of Michigan and Ohio, *by* J. A. Fagerstrom, $2.00 (M42-204)

205 Comparative study of the Castle River and other folds in the Eastern Cordillera of Canada, *by* D. K. Norris, $2.00 (M42-205)

206 Geomorphology and multiple glaciation in the Banff area, *by* N. W. Rutter, $2.00 (M42-206)

207 Geology of the resurgent cryptoexplosion crater at Mistastin Lake, Labrador, *by* K. L. Currie, $2.00 (M42-207)

208 The geology and origin of the Faro, Vangorda and Swim concordant zinc-lead deposits, Central Yukon Territory, *by* D. J. Tempelman-Kluit, $3.00 (M42-208)

209 Redescription of *Marrella splendens* (Trilobitoidea) from the Burgess Shale, Middle Cambrian, British Columbia, *by* H. B. Whittington, $3.00 (M42-209)

210 Ordovician trilobites from the central volcanic mobile belt at New World Island, northeastern Newfoundland, *by* W. T. Dean, $2.00 (M42-210)

211 A Middle Ordovician fauna from Braeside, Ottawa Valley, Ontario, *by* H. Miriam Steele and G. Winston Sinclair, $2.00 (M42-211)

212 Lower Cambrian tribolites from the Sekwi Formation type section, Mackenzie Mountains, Northwestern Canada, *by* W. H. Fritz, $4.00 (M42-212)

213 Sequence of glacial lakes in north-central Alberta, *by* D. A. St-Onge, $2.00 (M42-213)

214 Classification and description of copper deposits, Coppermine River area, District of Mackenzie, *by* E. D. Kindle, $4.00 (M42-214)

215 Brachiopods of the Arisaig Group (Silurian-Lower Devonian) of Nova Scotia, *by* Charles W. Harper, Jr., $5.00 (M42-215)

217 The geology and petrology of the alkaline carbonatite complex at Callander Bay, Ontario, *by* John Ferguson and K. L. Currie, $2.00 (M42-217)

218 Keeweenawan volcanic rocks of Michipicoten Island, Lake Superior, Ontario (41N): An eruptive centre of Proterozoic age, *by* R. N. Annells, $0.00 (M42-218)

219 Lower Cretaceous Bullhead Group, between Bullmoose Mountain and Tetsa River, Rocky Mountain Foothills, Northeastern British Columbia, *by* D. F. Stott, $0.00 (M42-216)

221 Chitinozoa and Acritarcha of the Hamilton Formation (Middle Devonian), southwestern Ontario, *by* J. A. Legault, $4.00 (M42-221)

222 Contributions to Canadian Paleontology, *by* D. E. Jackson, *et al.*, $6.00 (M42-222)

224 Carboniferous and Permian stratigraphy of Axel Heiberg Island and western Ellesmere Island, Canadian Arctic Archipelago, *by* R. Thorsteinsson, $6.00 (M42-224)