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Glaziallimnische Umwelt eines Teils der Oak Ridge-Moränen im Süden von Ontario

Robert Gilbert

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Article abstract

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GLACILACUSTRINE ENVIRONMENT OF PART OF THE OAK RIDGES MORAINE, SOUTHERN ONTARIO

Robert GILBERT, Department of Geography, Queen's University, Kingston, Ontario, K7L 3N6, gilbertr@qsilver.queensu.ca.

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ABSTRACT Glacilacustrine sediments in a 112 m core recovered from the Oak Ridges Moraine near Vandorf, Ontario are used to assess the environment at the time of deposition. Varves in the upper 23.7 m are of two types: thinner (20 - 110 mm) varves in groups of 29 and 23 at two levels. These are dominated by deposition of silt in summer, with lesser amounts of laminated silts and sands representing turbidity current deposition. Thicker (0.18 - 1.02 m) varves at the base and top of the deposit as well as in a group of 27 between the thin varves have a greater fraction in summer of coarser sediment deposited from gravity flows. Winter deposits of both are dominated by the clay-size fraction and most show at least one parting of silt or sand associated with periods of increased meltwater inflow during winter. Carbonate content varies from 25 - 55% with the highest proportion in the thinner deposits in winter and in the summer deposits of thin varves. It is proposed that a large, deep (greater than 100 m at least in the early phases) glacial lake was dammed on the Oak Ridges Moraine between the retreating Simcoe and Ontario lobes to the north and south, respectively, and the Niagara escarpment to the west. This lake existed as a relatively stable feature for at least 100 years.

RÉSUMÉ *Le mileu glaciolacustre d'une partie de la Moraine d'Oak Ridge, dans le sud de l'Ontario.* Une carotte de 112 m de sédiments glaciolacustres en provenance de la Moraine d'Oak Ridge, près de Vandorf, en Ontario, a servi à reconstituer le milieu à l'époque de sa mise en place. Les varves des 23,7 m supérieurs sont de deux types. Les varves fines (20-110 mm), en groupes de 29 et de 23 à deux niveaux, sont caractérisées par le dépôt de limon en été, avec de moins grandes quantités de silt et de sable laminé, ce qui témoigne d'un dépôt dans un courant de turbidité. Les varves plus épaisses (0,18-1,02 m) situées à la base et dans la partie supérieure du dépôt, ainsi que dans un groupe de 27 varves situé entre les varves fines, comprennent davantage de sédiments plus grossiers déposés en été à partir de glissements de terrain. Les dépôts d'hiver dans les deux cas sont caractérisés par la fraction argileuse et la plupart montre au moins un plan de séparation de silt ou de sable associé à des périodes d'augmentation du débit d'eau de fonte pendant l'hiver. La teneur en carbonates varie de 25 à 55% avec les proportions les plus élevées dans les dépôts les plus minces d'hiver et dans les varves fines de l'été. Nous supposons qu'un grand lac glaciaire profond (de plus de 100 m au moins au cours des premières phases) a été barré par la Moraine d'Oak Ridge, entre les lobes récessifs de Simcoe et d'Ontario, respectivement au nord et au sud, et l'escarpement de Niagara, à l'ouest. Ce lac est demeuré une entité relativement stable pendant au moins 100 ans.

ZUSAMMENFASSUNG *Glaziallimnische Umwelt eines Teils der Oak Ridge-Moränen im Süden von Ontario.* Glaziallimnische Sedimente aus einem 112 m langen Bohrkern von der Oak Ridge-Moräne bei Vandorf, Ontario, dienen bei der Bestimmung der Umwelt zur Zeit der Ablagerung. In den oberen 23.7 m gibt es zwei Typen von Warwen: Dünnere Warwen (20 - 110 mm) in Gruppen von 29 und 23 in zwei Niveaus. Diese sind von Schlammablagerung im Sommer beherrscht, mit geringeren Mengen von blättrigem Schlamm und Sand, was eine Ablagerung bei Dichtigkeitsströmung bedeutet. Dickere Warwen (0.18 - 1.02 m) an der Basis und im oberen Teil der Ablagerung wie auch in einer Gruppe von 27 Warwen zwischen den dünnen Warwen enthalten einen größeren Teil von gröberem Sediment, das im Sommer während Erdrutschen abgelagert wurde. Die Winter-Ablagerungen sind in beiden Fällen von der Lehm-Fraktion beherrscht, und die meisten weisen mindestens einen abgeteilten Strang von Schlamm oder Sand auf, den man auf Perioden verstärkten Schmelzwasserflusses während des Winters zurückführt. Der Gehalt an Karbonaten variiert von 25 - 55 % mit dem höchsten Anteil in den dünneren Ablagerungen im Winter und in den Sommer-Ablagerungen dünner Warwen. Es wird angenommen, daß ein großer, tiefer (über 100 m, mindestens in der frühen Phase) glazialer See durch die Moräne von Oak Ridge eingedämmt wurde, zwischen den jeweils nach Norden und Süden zurückweichenden Loben von Simcoe und Ontario und dem Niagara-Steilhang nach Westen. Dieser See existierte in relativ stabiler Form mindestens hundert Jahre lang.

INTRODUCTION

The Oak Ridges Moraine (ORM) in south central Ontario (Fig. 1 inset) was the locus of deposition over a relatively long period of time, especially associated with the Simcoe and Ontario lobes of the Laurentide Ice Sheet to the north and south, respectively (Chapman and Putnam, 1966; White, 1975; Duckworth, 1979; Sharpe *et al.,* 1994b). As the ice withdrew from the moraine between about 13.5 - 12.5 ka BP a complex geography of ice-dammed, ice-contact, and proglacial lakes formed between the ice lobes and the Niagara Escarpment to the west (Chapman, 1985). Mapping of these lakes in detail is impossible because much of their shorelines was along ice fronts and so they have not been preserved; our understanding of their paleogeography comes mainly from the deep-water glacilacustrine deposits throughout the moraine. This paper reports on this glaciolacustine sedimentary environment from an assessment of a core recovered from the ORM.

THE CORE

The Vandorf core (UTM 4874000 630000) is from the narrow western arm of the ORM (Fig. 1a), 1.5 km north of the crest at an elevation of 309 m a.s.l. (Fig. 1b). The 70-mm diameter core was recovered by rotary drilling from 21 - 132.9 m below the surface (290 - 176 m a.s.l.) in 1.5 m long sections with missing portions up to 3 m between respective sections, some represented by small bulk samples of mixed sediment. The core was split and logged in the field and returned to the laboratory where it was rewetted to obtain maximum contrast of the laminations for photography and subsampled for sedimentary texture and carbon content.

Seven sedimentary facies can be distinguished in the core (Table I). The diamictons (facies 3 and 5) are thought to be the Newmarket drift overlying earlier non-glacial or glacilacustrine deposits (facies 1 and 2), and ascribed to a near-ice or ice-contact environment during the Port Bruce Stade. Facies 4 between the diamicton beds represents an ice-proximal or subglacial glacifluvial and glacilacustrine environment of the same period. The thick deposit of massive, layered and cross-bedded sands (facies 6) originated as subaqueous fans at the mouths of high-energy streams emanating from the ice lobes. These are distinguished from the sands below (facies 4) by a higher degree of sorting and coarser grain size representing a more proximal environment (Fig. 2).

TABLE I

Generalized log of Vandorf core, Oak Ridges Moraine

Facies	Depth below surface (m)	Description
	21.4 (top of core)	
7		Varves - silt and sand summer layers, clay-rich winter layers
	44.7	
6		Medium and fine-grained sand; massive, layered and graded
	ca. 70	
5		Compact diamicton of silt-clay matrix and clasts to 2 cm diameter
	72.6	
4		Massive, layered and graded medium to fine sand
	86.2	
3		Compact diamicton of silt-clay matrix and clasts to 5 cm diameter
	108.2	
2		Massive and graded sands interlayered with sand-clay rhythmites and thin diamicton layers
	125.5	
1		Rhythmites of cross-laminated silt and sand and clay caps. Varves cannot be distinguished
	132.9 (bottom of core)	

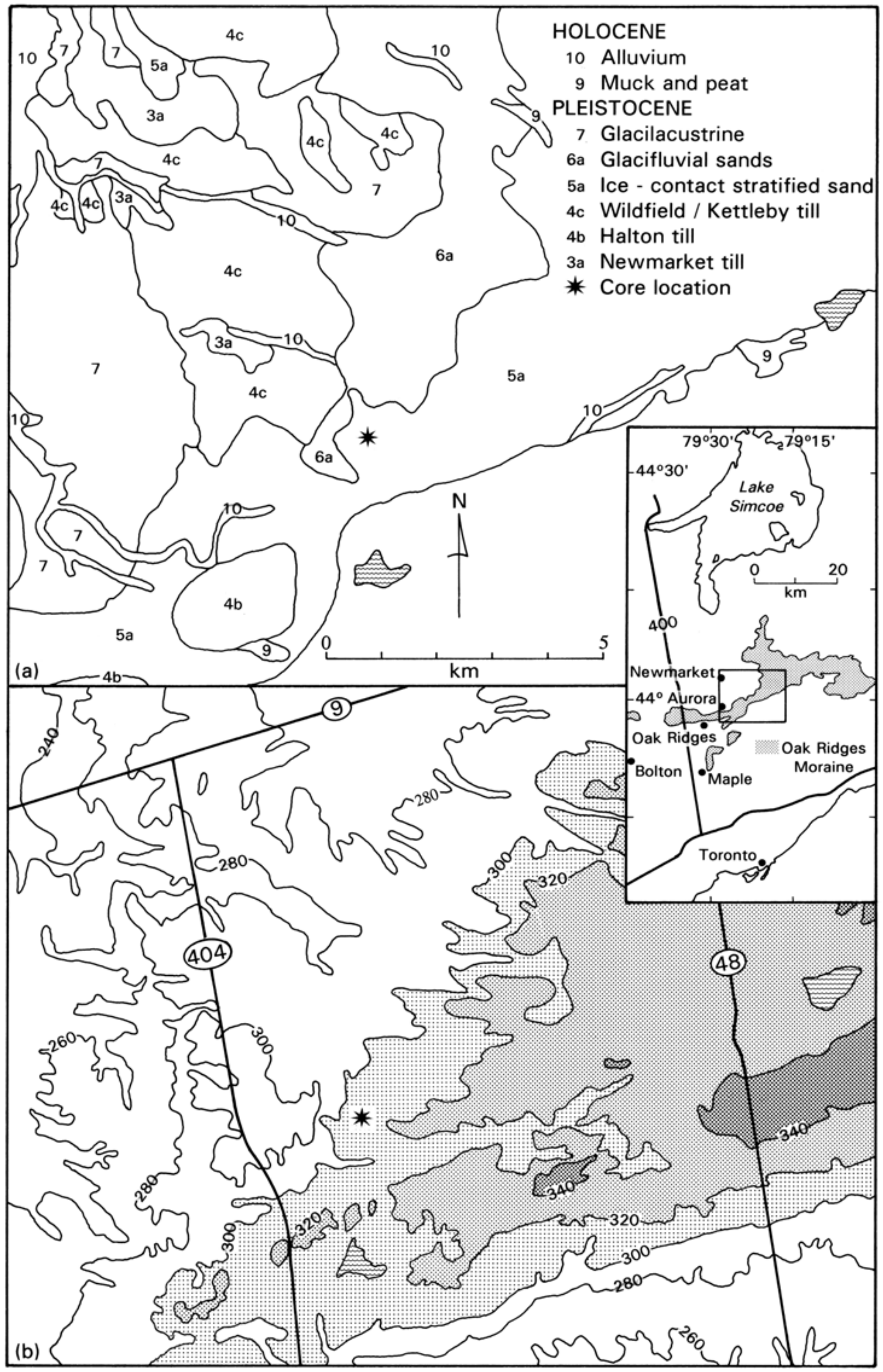
The uppermost facies 7 is made up of glacilacustrine sediments consisting of varves mainly of silt and sand in summer with clearly distinguished clay caps in winter. It is these sediments that are examined in detail in this paper to assess the paleoenvironment of this section of the ORM during the last phases of deglaciation.

GLACILACUSTRINE SEDIMENTS

The detailed log of facies 7 (Fig. 3) shows that from near the top of the core at 21.38 m to 44.75 m depth the sediments are made up of rhythmites varying in thickness from 20 mm to 1.02 m. Each consists of a thicker silty layer,

FIGURE 1. (a) Surficial materials in vicinity of the core location. The ice-contact stratified sands delimit the boundary of the Oak Ridges Moraine (Sharpe *et al.*, 1994a). (b) Topography (contours in metres) in the vicinity of the core location from NTS topographic maps. Inset shows the western section of the ORM.

(a) Les dépôts de surface dans les environs du site de sondage. Les sables stratifiés de contact glaciaire délimitent la Moraine d'Oak Ridges (Sharpe et al., *1994a). (b) La topographie (courbes en mètres) dans les environs du site de sondage. Le carton illustre la partie ouest de la Moraine d'Oak Ridges.*



some with sand intermixed or as distinct massive or laminated and cross-laminated layers, and a thinner cap of clay with some silt and sand, again intermixed or as distinct laminae. Based on their appearance and sedimentary character described below, these rhythmites are interpreted as varves, although this cannot be confirmed independently by other dating techniques.

Eight missing segments (Fig. 3) lost during the coring operation account for 6.7 m (29%) of the 23.37 m of facies 7. In establishing a chronology of facies 7, varve thicknesses in missing sections were estimated from the thicknesses of those on either side. Except at 24 and 40 m where an estimated eleven and six small varves, respectively, were lost, the other breaks account for zero to four varves missing in

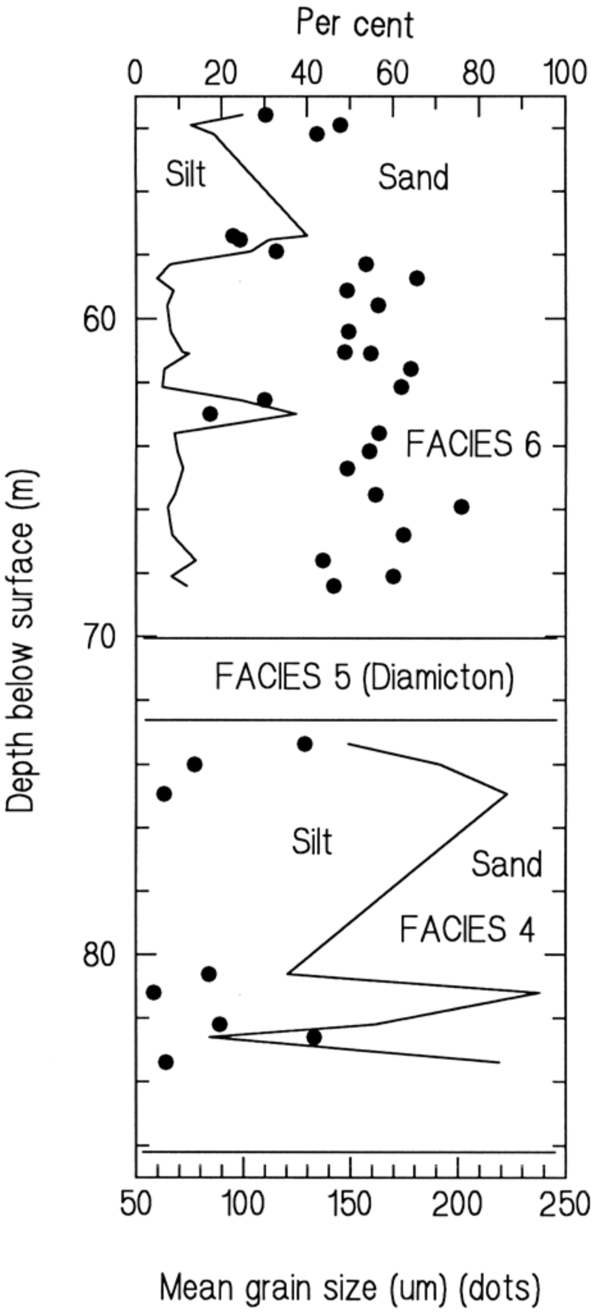


FIGURE 2. Mean grain size and percent sand and silt in facies 4 and 6 of the Vandorf core.

Granulométrie moyenne et pourcentage de sable et de silt dans les faciès 4 et 6 de la carotte de Vandorf.

whole or in part. That is, of the 98 varves estimated to occur in facies 7, 67 are complete; the top or bottom portions of 14 more were missing, and an estimated 17 varves are missing completely.

Thus, the glacilacustrine setting in which these sediments were deposited probably existed for about 98 ± 8 years. In addition, below the lowest varve (1) there is a non-erosional transition to the massive and layered sands of facies 6 (a portion of the upper part of which was not recovered - Fig. 3), which were also probably deposited in a subaqueous environment, close to or beneath a glacier during the early stages of the lake. Although these sediments are relatively thick (about 25 m), they were probably deposited rapidly in one or a few melt seasons (*cf.* Eyles *et al.*, 1987 who ascribe up to 50 m of sands in the Fraser Valley glacial lake to quasi-continuous turbidity currents), so that the actual duration of the lake at the Vandorf core site is estimated between about 92 and 108 years. As well, the sands of facies 4 were also deposited in water before the final retreat of the glacier that deposited the diamicton of facies 5, so elsewhere, especially to the west where the Simcoe and Ontario lobes parted earlier, a lake may have existed for a longer period. The final stages of glacial lakes were below the level of the Vandorf core in the Holland River Valley to the northwest (Duckworth, 1979)

The varves represent two sedimentary environments. Relatively thin varves, less than about 130 mm thick, here referred to as type I (Fig. 4) occur at two levels in the core, 23.45 - 24.52 m (varves 71 - 93) and 39.03 - 41.38 m (varves 14 - 42). Thicker varves having evidence of high energy sedimentary processes comprise type II.

TYPE I VARVES

The mean thickness of type I varves is 81 mm (lower group) and 46 mm (upper) which is greater than in most modern glacilacustrine settings, but comparable to those of some of the large Pleistocene glacial lakes (Table II). The sedimentary characteristics of type I varves include the following. The summer layers consist almost entirely of silt and clay-sized sediment (Fig. 3) with the latter comprising about 40%. Structure varies from very faintly laminated as in varve 39 to 8 - 10 rhythmites as in varves 88 and 91 (Fig. 5). here both laminated and massive sediments occur in the same summer, the latter tend to occur earlier and to be slightly finer-grained (for example, varves 89 and 90), although the transition from winter to summer is normally abrupt (but see 39-40) as is the summer-to-winter transition. A few type I varves contain graded laminations with minor amounts of fine sand at the base, and one in varve 89 (Fig. 5a) contains cross-laminated fine sand and silt in a layer about 3 mm thick.

The winter layers of type I varves are thin compared to the summer, with the mean thickness of the lower and upper sections 11.7 and 7.0 mm, respectively. Clay content is higher (about 60 to 75% - Fig. 3) and sand is absent. In almost all of the winter layers there is evidence of input of silt, either creating minor partings in mid-winter (for example, varves 39 and 89 - Fig. 5), or contributing a significant silty deposit (varve 90). In the case of the latter, it is possible, although unlikely, that a varve occurs between those labelled 90 and 91. This is typical of the winter layers of varves (Shaw *et al.*, 1978) and indicates minor meltwater

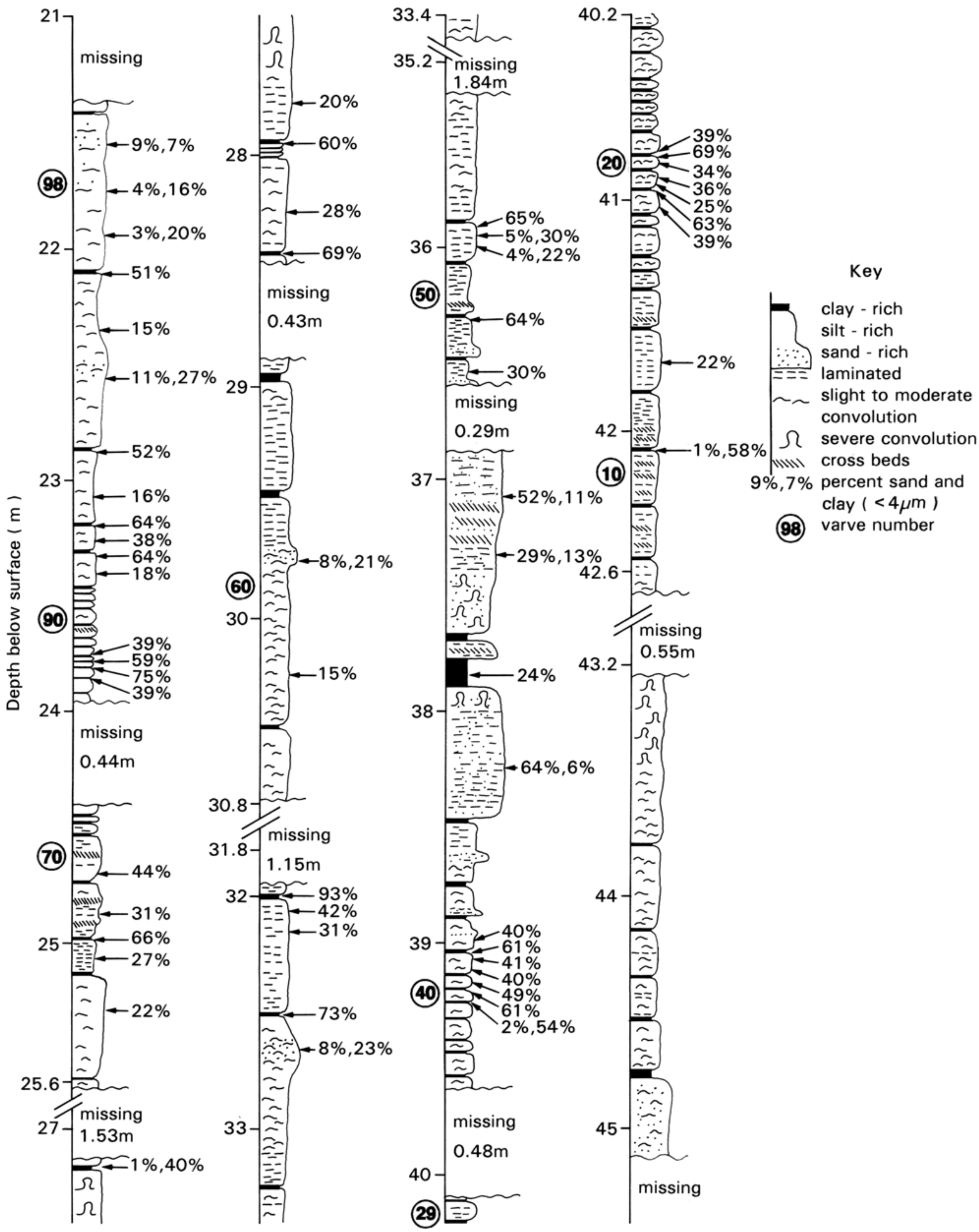


FIGURE 3. Log of facies 7 of the Vandorf core. Values in per cent are of sand and clay-size (< 4 μm). Where sand is absent, only the per cent clay size is indicated. Varve numbers are circled.

Données (relevé) du faciès 7 de la carotte de Vandorf. Les valeurs en pourcentages s'appliquent aux sable et à l'argile (< 4 μm). En l'absence de sable, seul le pourcentage de l'argile est donné. Les nombres de varves sont encerclés.

inputs during mid-winter, associated with short periods of warm weather, probably from rain on snow in the warm sectors of cyclonic storms.

TABLE II

Mean thicknesses of selected glacilacustrine varves (= annual rates of sedimentation)

Lake	Class(*)	Thickness (mm) (**)	Source
Harrison, British Columbia	DP	2 P	Desloges and Gilbert (1991)
Stave, British Columbia	DP	3	Gilbert and Desloges (1992)
Hector, Alberta	DP	1.2 - 5.4	Leonard (1985)
		1 - 14	Smith (1981)
Moose, British Columbia	DP	1 - 6.5	Desloges and Gilbert (1995)
Bondhusvatn, Norway	PP	2 - 5	Østrem and Olsen (1987)
Schomberg, Ontario	IC	6 - 25	White (1975)
		up to 100	Chapman and Putnam(1966)
Ape, British Columbia	ID	25 P; 0.80 D	Gilbert and Desloges (1987)
Bowser, British Columbia	DP	7 - 33 P; 3 - 13 D	Gilbert *et al.* (in press)
Priest, Washington	ID	*ca.* 40	Waitt (1984)
		ca 200 - 400 when jokulhlaup inflow	
Lillooet, British Columbia	DP	93 P; 7.0 D	Gilbert (1975); Desloges and Gilbert (1994)
Steep Rock Lake, Ontario	IC	8 - 202	Antevs (1951)
Stockholm, Sweden	IC	50 - 150	de Geer (1912)
Okanagan, British Columbia	IC or IP	35 - 430	Shaw (1977)
Vandorf, Ontario	ID	20 - 1020	this study

(*) ID refers to ice-dammed lakes, IC to ice-contact, PP to proximal proglacial, and DP to distal proglacial lakes

(**) P refers to proximal and D to distal to the point of inflow in the lake.

These sedimentary characteristics suggest a quiet, deep-water, relatively distal environment. The sediment input must have been high compared to modern glacial lakes where concentrations of sediment in the water column vary from a few tens to several hundred milligrams per litre (Gilbert and Desloges, 1987), but most was deposited from suspension in the water column. Turbidity currents creating graded or cross-laminated deposits and transporting sand to the core site were less common compared to their near daily occurrence in some modern glacial lakes (Gilbert, 1975; Weirich, 1986). Where laminations do occur, their pattern suggests the occurrence of eight to ten periods of enhanced inflow associated with warmer temperatures or rainfall events. The massive-to-laminated transition in some varves (for example 89 -- Fig. 5) suggests that nival melt was a less important agent of sediment input than events later in the summer, probably associated with the rapid melting of more sediment-laden glacial ice.

TYPE II VARVES

Type II varves comprise 44 of the 98 varves. They are significantly thicker than those of type I with mean thickness 446 mm, and the thickest more than 1 m (Fig. 6). These are among the thickest varves recorded (Table II) and indicate very high rates of sedimentation. Among their sedimentary characteristics are the following. Texture is considerably coarser with up to 64% sand content in the summer layers (Fig. 3; Fig. 7e), although a number of the thickest varves (for example 57 - Fig. 7d) have no sand at all. Structure varies from massive (as varve 96 - Fig. 7a) to well laminated in both and sands and silts. Some of the laminae are graded; a few reverse-graded layers occur in the coarsest varves; up to three cross- bedded units occur in the summer layers, and a number of the summer layers are significantly contorted (as varve 47 - Fig. 7e). The coarser grain size and thicker beds (Fig. 3) indicate the presence of more powerful gravity flow processes (including grain flow as evidenced by the reverse grading) in type II varves as compared to type I.

A common feature of the laminations are regular rhythmites clearly defined on a millimetre scale as in varve 68 (Fig. 7b) and more subtly distinguished on a centimetre scale as in varves 64 and 57 (Fig. 7c and d). For example, of the latter, 34 can be distinguished in varve 57 and 53 in varve 56 (mean thickness 11.8 and 6.7 mm, and occupying 81% and 50% of the total summer thickness, respectively).

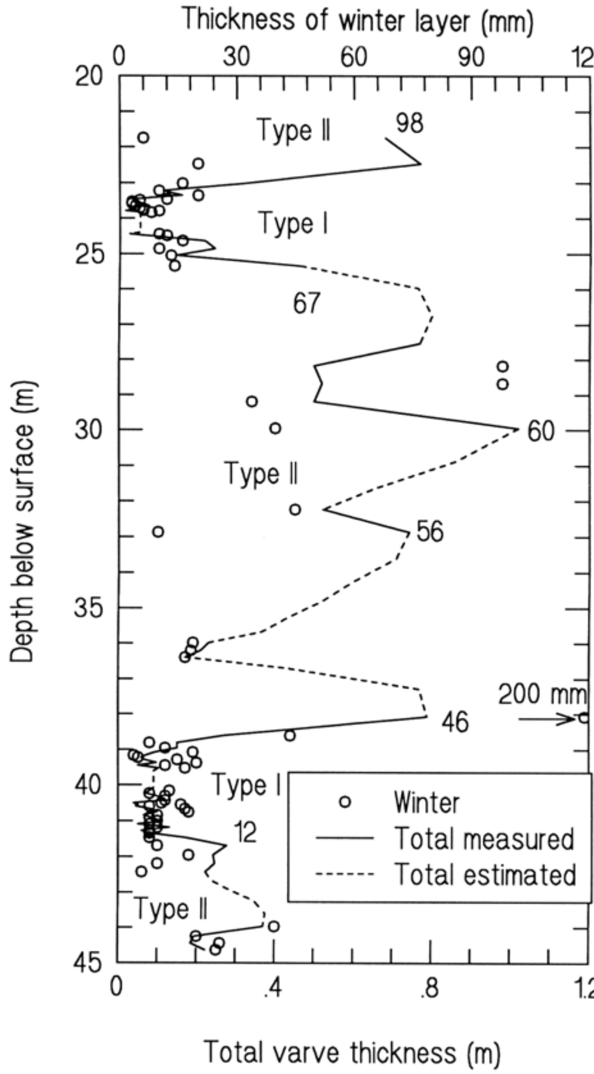


FIGURE 4. Total varve thickness measured from the top of the winter layers, and thickness of the winter layers (at ten times the total thickness scale) that cap varves in facies 7 of the Vandorf core.

Épaisseur totale des varves mesurée à partir de la partie supérieure des varves d'hiver, et épaisseur des couches d'hiver (dix fois l'échelle de l'épaisseur totale) qui coiffent les varves du faciès 7 de la carotte de Vandorf.

These may represent the warm, clear days that give rise to strong daily pulses of meltwater and sediment at the peak of the melt season and that distribute them by daily katabatic winds in a proximal glacilacustrine environment (*cf.* Sunwapta Lake - Gilbert and Shaw, 1981).

At several locations (for example in varve 96 - Fig. 7a) laminated and massive sediments appear side by side in the core. This is unlikely an artifact of coring, as sediments above and below are undisturbed. It is possible that these represent the edge of channels or small scours eroded by the passage of relatively powerful turbidity currents, and that are subsequently filled (perhaps by the tail of the same current) with laminated sediments. Channels are reported in glacilacustrine (Forel 1885; Houbolt and Jonker, 1968; Brodie and Irwin, 1970; Irwin, 1980; Lambert and Giovanoli, 1988) and glacimarine environments (Gilbert, 1983; Prior and Bornhold, 1989; Phillips and Smith, 1992) where they are at a scale of metres to tens of metres. However, it is possible that only a small part of a channel is recorded in the Vandorf core. Nevertheless, loading and rip-up structures that are a measure of high-energy sedimentary processes are uncommon in facies 7. The best examples are rip-up clasts of clay from the winter layer of varve 46 and loading structures on the top of the same winter layer, both associated with the sands of the next melt season (Fig. 7e).

With a few exceptions (for example in varve 63 - Fig. 7c - and most remarkably varve 46 - Fig. 7e), the winter caps of type II varves are not proportionally thicker than those of type I (Fig. 4). This suggests that the sediment in the water column is not greatly different between the years in which type I and II varves were deposited and that much of the difference in total thickness is due to deposition from gravity flows.

Thick winter caps have been ascribed to a distal environment where fine-grained deposition all occurs in a short period at the peak of the melt season (Ashley, 1975). Since both thick and thin caps occur in the Vandorf core this explanation is less viable here. However, where both thin and thick caps occur at the same site in Lillooet Lake, it was shown (Gilbert, 1975) that winters with thick caps followed a large, late autumn inflow event that began and ended abruptly. It was proposed that the consequence was a pulse of sediment enhanced by the hysteresis effect on rising stage (Østrem, 1975) that was not flushed from the lake by later flow, but that remained in the water column to settle through the winter. In maritime alpine settings, these late floods that flush the largely dormant glacial river system are the result of autumn cyclonic storms bringing snow and then rain on snow (Desloges and Gilbert, 1994). In southern Ontario, such events are presently associated especially with the influence of tropical storms from the Gulf of Mexico, and may have also been the case irregularly at the close of the Pleistocene, despite the blocking influence of high pressure over the Laurentide Ice Sheet.

The transitions from summer to winter and winter to summer are more abrupt in the type II varves, both where coarse-grained massive sediment is deposited in the autumn or spring (Fig. 7e) and where silts dominate (Fig. 7a and b). This is seen simply as the consequence of a more vigorous nival melt early in the summer, and glacial melt later, both bringing larger loads of sediment earlier and later in the melt season.

Almost all the type II winter layers showed the same partings of coarser sediment as the type I. The 60-mm thick sand layer in varve 46 (Fig. 7e) is probably the result of a single turbidity current depositing a graded bed, cross laminated at the base, and containing numerous rip-up clasts of clay in the more horizontally layered sand above. Larger but similar beds in Lake Okanagan were ascribed by Shaw

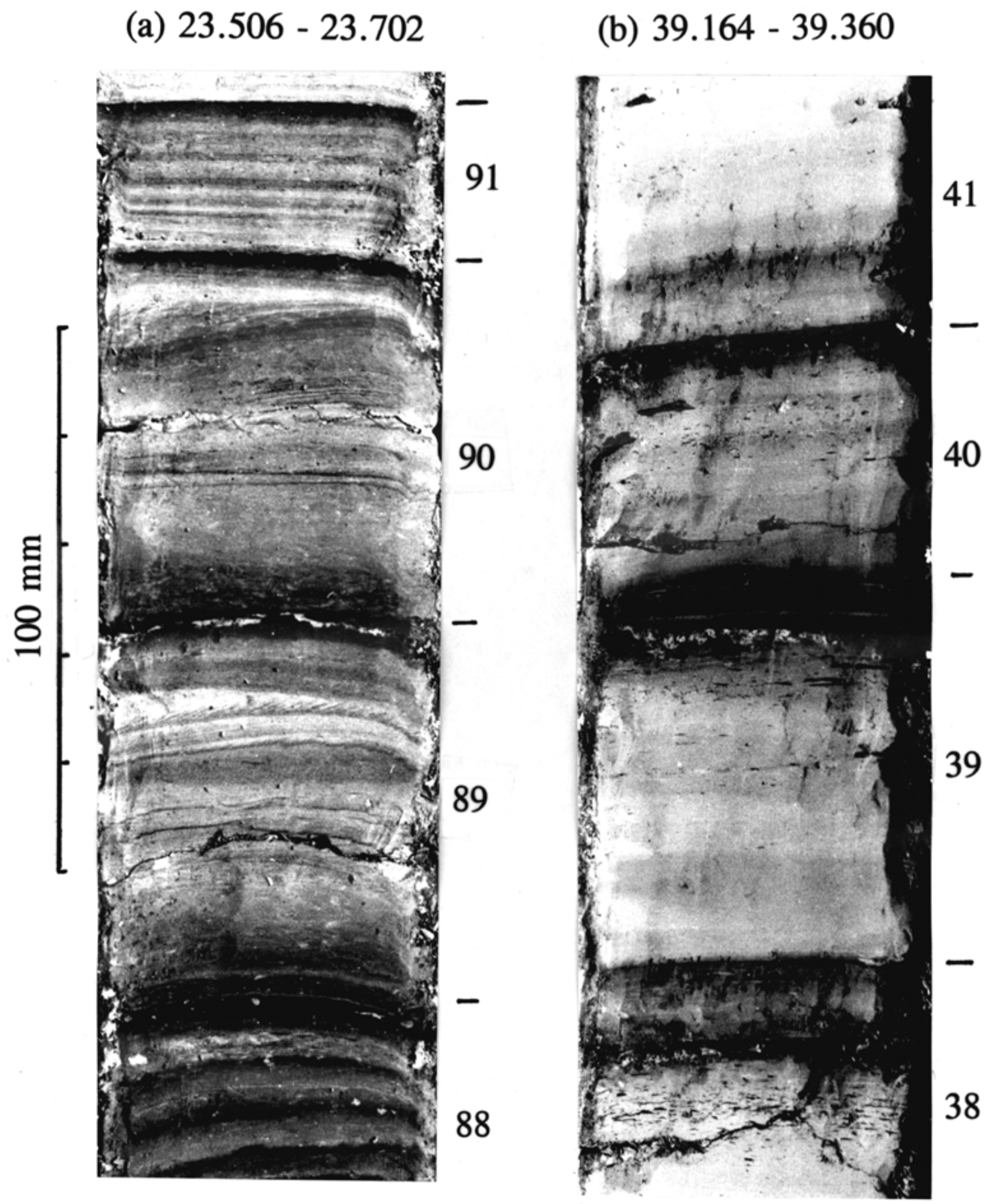


FIGURE 5. Examples of type I varves from facies 7 of the Vandorf core. Numbers at top refer to depth in metres; those on the side to the varve number.

Exemples de varves du type I (faciès 7) de la carotte de Vandorf. Au-dessus, les chiffres se rapportent à l'épaisseur ; sur le côté, ils donnent le numéro de la varve.

(1977) to input from jökulhlaups during winter. This may have been the case here, but more likely it is the consequence of a short period of very warm weather. Note that other inflow events occurred in the autumn, early winter (perhaps providing the fine sediment for the thick clay layer as described above) and soon before the onset of melt in the spring of year 46-47.

CARBONATE IN THE VARVES OF FACIES 7

The loss on ignition between 500 and 1000°C of 120 samples was used to calculate the carbonate content (Dean, 1974) of the sediments of facies 7. The results shown in Figure 8 are comparable with carbonate levels in other glacilacustrine deposits in the region (White, 1975 -- 40 to 50%; Chapman and Putnam, 1966 -- 50%). Statistically, there is no significant trend through time, nor is there a difference between winter and summer content of type I varves, or between winter content of type I and II varves. However, type II varves contain significantly ($p = 0.05$) less carbonate in their summer layers than in the winter layers and than in the summer layers of type I. In addition there is a significant increase through time in carbonate in the summer layers of the middle group of type II varves (39.03 - 24.05 m) as shown in the trend line in Figure 8. There is a weak ($r^2 = 0.754$) negative correlation between mean grain size and carbonate content, reflecting the higher silt content in glacial till derived from carbonate bedrock as compared to igneous and metamorphic rock.

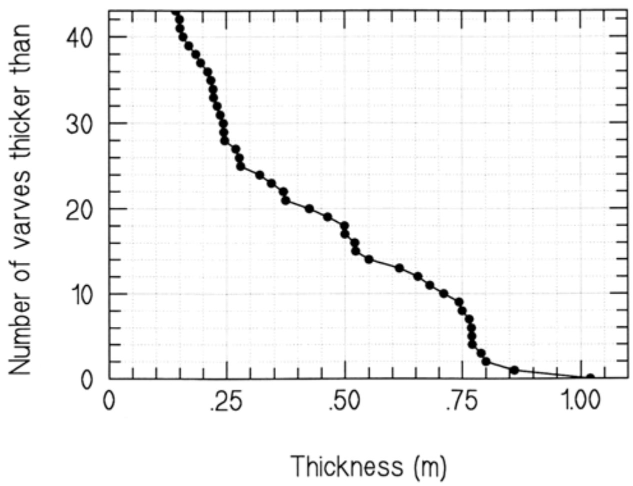


FIGURE 6. Excedence series of the estimated and measured thickness of the type II varves from facies 7 of the Vandorf core.

Séries de varves du type II d'épaisseur exceptionnelle mesurée et estimée, faciès 7 de la carotte de Vandorf.

There are two potential sources for the carbonate deposited in a lake. The first is the autochthonous carbonate deposited as marl from supersaturated solution in the inflowing water. Since this is largely produced by warming of the epilimnion during summer (Thompson *et al.*, 1990), and since ice-contact and ice-dammed lakes are likely to remain cold even in summer (Gilbert, 1971; Churski, 1973) unless the region of contact is small (Gilbert and Desloges, 1987), this is probably not an important mechanism for the sediments in the Vandorf core. The relatively small differences between winter and summer (*cf.* non-glacial lakes - Brunskill, 1973; Dell, 1973) supports this supposition.

The second source is allochthonous carbonate delivered as particulate matter eroded from carbonate rocks in the region. The border between the Palaeozoic limestones that underlie ORM and the igneous-metamorphic complexes of the Canadian Shield lies 75 km to the north of the core site. It is probable that most of the carbonate in the Vandorf core is derived rock flour created by glacial erosion or fluvial abrasion of the Palaeozoic limestones. The lower carbonate content in the lowest of the middle range type II varves (Fig. 8) may reflect greater contribution from the north (the Simcoe Lobe) and longer-distance transport under higher energy conditions of other rock types from Shield sources during this period of increased sediment input (thicker varves).

THE PALEOENVIRONMENT

Clearly, from one core it is not possible to reconstruct the paleogeography of the lake in which the sediments were deposited. Nevertheless, the sediments provide clues to conditions at their time of deposition which may be related to existing regional geographic reconstructions.

First, even the latest varves at the top of the column were deposited in deep water below wave base and with slopes downward from the point or points of inflow sufficient to allow turbidity currents to spread over the site (even if subsequently travelling upslope some distance to the core site due to inertia - Pantin and Leeder, 1987). Chapman's (1985) model proposes an interlobate lake (Lake Schomberg - White, 1975; Chapman and Putnam, 1966) dammed within the Simcoe Lobe on the north, the Ontario lobe filling in the gaps over the crest of the moraine along the south, and the Niagara escarpment on the west where sill depths were 367 m a.s.l. at Action and later 350 m at Campbellville. Allowing for isostatic depression, the elevation of the water surface and depth at Vandorf would have been 383 m a.s.l. and about 120 m in the early stage, and 326 m a.s.l. and about 35 m in the late stages of deposition if the lake fell during that period, 100 m if it did not. Presuming the lake was at least partially free of bergs and lake ice during at least a short period during the melt season (*cf.* the evidence from ice push in glacial Lake Iroquois a short time later - Gilbert *et al.*, 1992), the maximum effective fetch would have been about 30 km from the west southwest and the wave base not in excess of about 15 m (Sly, 1978), well above the depths postulated above.

In the early phases of lake development the sands of facies 4 and 6 were deposited at the mouths of meltwater channels beneath or close to the ice faces. Duckworth (1979) shows that the flow was predominantly westward from ice to the northeast and southeast. Apparently the ice retreated sufficiently rapidly that within a few years fully glacilacustrine conditions had become established and these were to last about 100 years at this site.

Variation in rates of glacilacustrine sedimentation at a site as measured in varve thickness may be ascribed to one or more of four causes. First, as the glacier retreats, rates decrease as sites become progressively distal (Scheidegger, 1965; Gilbert and Desloges, 1987). Since the rates at Vandorf change so rapidly within several years and there is no detectable trend though time (Fig. 4), this mechanism probably played a minor role and the lake probably did not change greatly in area during the 100 years.

Second, the creation of a new outlet or failure of an ice dam leads to at least a partial draining of the lake and lowering of the water level. This is expressed in the sedimentary record by anomalous deposits (Gilbert and Desloges, 1987) from erosion of glacilacustrine sediments now located subaerally or in shallow water (*cf.* Gilbert, 1990). Although according to Chapman (1985), the lake fell 58 m between the Action and Campbellville stages, no evidence of this event is seen in facies 7 sediments at Vandorf.

Third, avulsion in input streams related to catastrophic changes in flow patterns in the glacier (Ashley, 1988), especially when associated with the tapping of reservoirs of sediment within the ice (Gilbert and Shaw, 1981), may instantaneously increase or decrease rates of accumulation at a given site. This may have been a factor at the Vandorf site, although there are normally several varves that may be

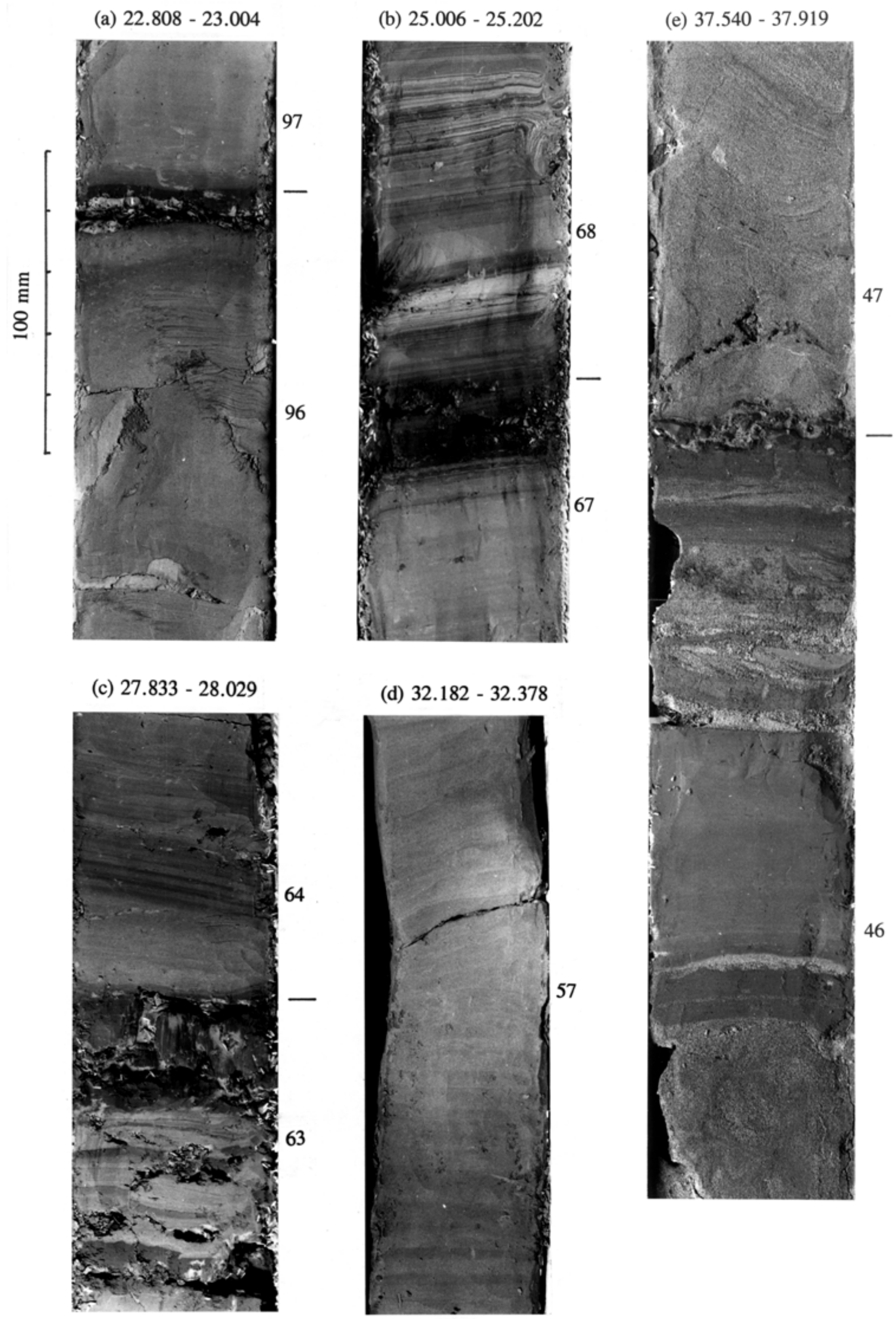


FIGURE 7. Examples of type II varves from facies 7 of the Vandorf core. Numbers at top refer to depth in metres; those on the side to the varve number.

Exemples de varves du type II du faciès 7 de la carotte de Vandorf. Au-dessus, les chiffres se rapportent à l'épaisseur ; sur le côté, ils donnent le numéro de la varve.

regarded as transitional between each type (Fig. 4), and it is difficult to postulate a gradual avulsion requiring several years to occur. As well, at least two periods of reduced input occur, requiring four avulsions.

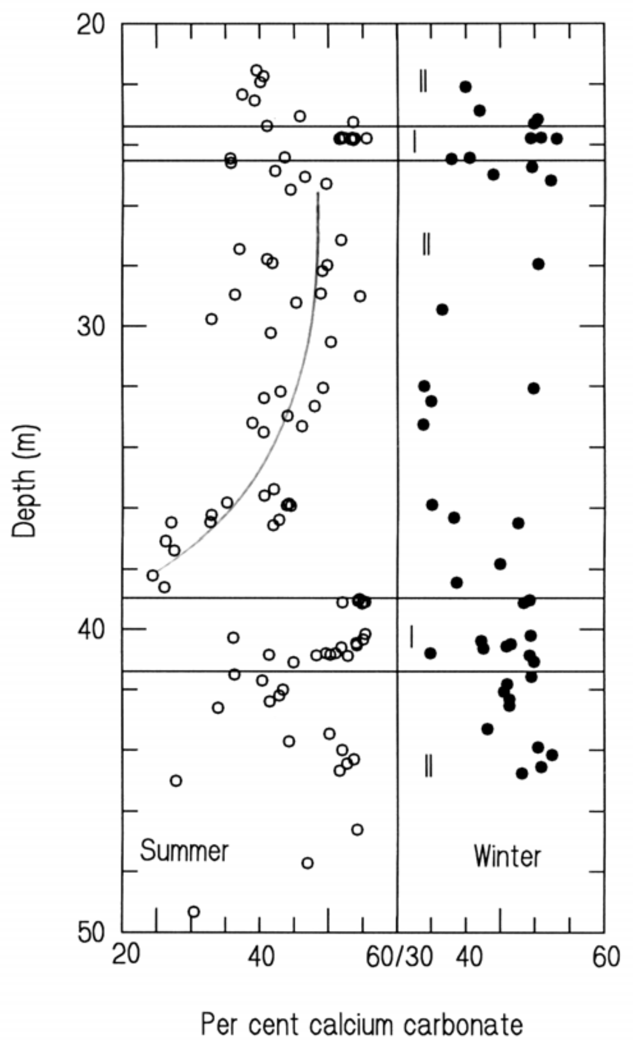


FIGURE 8. Loss on ignition between 500 and 1000 °C and corrected to loss of calcium carbonate by division by 0.44 (Dean, 1974) for type I and II varves in facies 7 of the Vandorf core.

Perte au feu entre 500 et 1000 °C et correction par division par 0,44 (Dean, 1974) en rapport à la perte en carbonate de calcium pour les varves de types I et II du faciès 7 de la carotte de Vandorf.

Fourth, varying rates of sedimentation are related to climatic and hydrologic changes controlling input to glacial lakes (Gilbert, 1975; Leonard, 1986; Desloges and Gilbert, 1994). If this were the major cause at the Vandorf site, then the fluctuations (almost up to an order of magnitude - Fig. 4) are greater than observed in most glacial lakes. On the other hand, the proximity of large, changing ice masses on two sides, responding to a rapidly moderating climate creates an environment unlike any at present. As discussed above, the sedimentary characteristics of facies 7 can be accounted for by invoking processes observed in modern lakes and the changes related to changing energy levels. As well, there is a rough periodicity in the thickness records within the series (29 type I varves, followed by 27 type II, and 23 type I) that suggests, rather than catastrophically changing control, a regularly fluctuating factor as might be provided by climatic changes.

Although there is no evidence in the core of the catastrophic draining of the lake in which these varves were deposited, between the present land surface and the top of the core at 21.4 m depth not retained for analysis consists of fine sand with little or no mud, except as weathered in the modern soil. This suggests a period of subareal exposure after draining in which the surficial sediments were winnowed principally by aeolian processes before vegetation became established on the surface. On the sandplain to the north of the core site there are numerous relic dunes up to 5 m high.

It is concluded that the Vandorf core record indicates the presence of a large, relatively deep and stable glacial lake that existed for about 100 years. Based on analogues in modern glacial lakes, sedimentation was determined by variations in meltwater input which governed sediment input and both were governed in turn by climatic processes.

FIGURE(S)

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