On the origin of the Oak Ridges Moraine[1]

P.J. Barnett, D.R. Sharpe, H.A.J. Russell, T.A. Brennand, G. Gorrell, F. Kenny, and A. Pugin

Abstract: Landscape analysis, mapping, sedimentology, shallow geophysics, and borehole data are integrated to better understand the complex landform–sediment geometries and event sequences of the Oak Ridges Moraine, southern Ontario. A model for the origin of the Oak Ridges Moraine is based on the recognition that the moraine is built on a high-relief, erosional surface (unconformity) consisting of drumlin uplands and a network of deep, steep-walled, interconnected valleys (tunnel channels). The development of the moraine is thought to have occurred in four stages: I, subglacial sedimentation; II, subaqueous fan sedimentation; III, fan to delta sedimentation; IV, ice-marginal sedimentation. The model traces the transition from subglacial to proglacial conditions during moraine formation and examines the order and timing of sedimentation. It is thought that the early stages of moraine construction are better exposed in the east; in the west, these stages are buried by later stages.

Résumé : Les études de paysage, cartographie, sédimentologie, géophysique de subsurface et des carottes de trous des sondages ont été menées conjointement pour chercher à mieux comprendre les configurations complexes des formes de relief–sédiments, et les séquences des événements qui ont affecté la Moraine d'Oak Ridges, dans le sud de l'Ontario. Un modèle interprétant l'origine de la Moraine d'Oak Ridges est fondé sur le fait que cette moraine fut édifiée sur une surface d'érosion (discordance) en terrain à topographie accentuée, comprenant des drumlins sur terres élevées et des vallées à parois subverticales interconnectées (chenaux tunnels). Le modèle propose un développement de la moraine en quatre phases : I, sédimentation sous-glaciaire; II, sédimentation d'un éventail sous-aquatique; III, sédimentation de l'éventail évoluant vers un dépôt deltaïque; IV, sédimentation en bordure d'un glacier. Le modèle retrace la transition de conditions sous-glaciaires à proglaciaires durant la formation de la moraine, et traite de l'ordre et de la chronologie du sédiment. Il apparaît que c'est dans le secteur oriental que les premières phases de l'édification de la moraine sont le mieux exposées; tandis que dans le secteur partie occidental, elles sont enfouies sous le sédiment des phases plus tardives.

[Traduit par la Rédaction]

Introduction

The Oak Ridges Moraine (ORM) is the most prominent, stratified moraine complex in southern Ontario. It is one of several linear moraines (e.g., Hartman, Harricana, Valley Heads, St. Narcisse) in the Great Lakes region (Fig. 1). The origins of these stratified moraines are poorly understood and to truly understand their genesis and landform character requires the application of multiple approaches (including subsurface surveys; e.g., Sharpe et al. 1992; Brennand and Shaw 1996). To what extent are these moraines the product of glaciofluvial and glaciolacustrine processes as opposed to ice-dynamic processes? Was sedimentation subglacial, ice supported, and (or) ice marginal? Was it time transgressive or synchronous? Was sedimentation rapid and sporadic or slow and more continuous? How does this knowledge allow one to improve predictions of lithofacies occurrence and transitions that are important to environmental reconstruction and, for example, hydrogeologic understanding?

Studies completed on the Hartman Moraine have identified glaciofluvial and glaciolacustrine features and sedimentological characteristics of meltwater floods (Sharpe and Cowan 1990; Sharpe et al. 1992). The Harricana Moraine is a glaciofluvial complex that may represent time-transgressive formation at receding ice margins (Veillette 1986) or synchronous but episodic, high-energy sedimentation within a conduit (Brennand and Shaw 1996). The Valley Heads Moraine formed from ice-marginal sedimentation downflow of tunnel channels now occupied by the Finger Lakes (Mullins and Hinchy 1989; Petruccione et al. 1996). Parts of the St. Narcisse Moraine are the product of subaqueous fan sedimentation into the Champlain Sea (Burbidge and Rust 1988).

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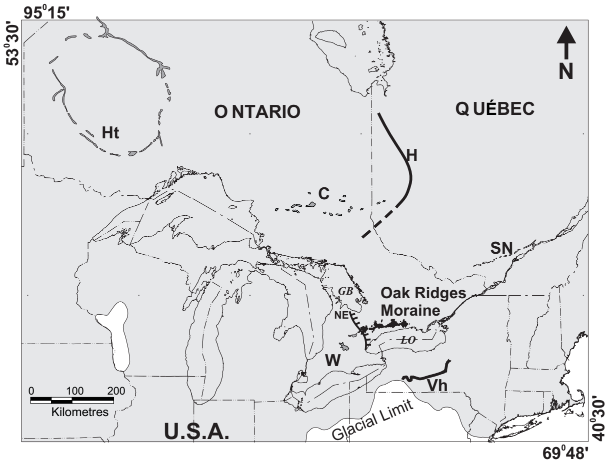
P.J. Barnett.[2] Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, ON P3E 6B5, Canada.
D.R. Sharpe. Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada.
H.A.J. Russell. Department of Geology, University of Ottawa, Ottawa, ON K1N 6N5, Canada.
T.A. Brennand. Department of Geography, Simon Fraser University, Burnaby, BC V5A 1S6, Canada.
G. Gorrell. Gorrell Resources Investigations, RR1, Oxford Mills, ON K0G 1S0, Canada.
F. Kenny. Ontario Ministry of Natural Resources, Peterborough, ON K9J 8M5, Canada.
A. Pugin. Institut F.-A. Forel, route de Suisse 10, CH-1290 Versoix, Switzerland, and Département de géologie, 13, rue des Marachers, 1211 Géneve 4, Switzerland.

[1] Geological Survey of Canada Contribution 1997239.
[2] Corresponding author (e-mail: barnetp@gov.on.ca).

Fig. 1. Location of the Oak Ridges Moraine and stratified moraines in the Great Lakes area. C, Chapleau Moraine; H, Harricana Moraine; Ht, Hartman Moraine; NE, Niagara Escarpment; SN, St. Narcisse Moraine; Vh, Valley Heads Moraine; W, Waterloo Moraine; *GB*, Georgian Bay; *LO*, Lake Ontario.



Purpose and approach

The purpose of this paper is to present a model for the formation of the Oak Ridges Moraine. The paper demonstrates that the moraine is built on a regional unconformity that, in part, controls the distribution and thickness of moraine sediments (e.g., Barnett 1995; Sharpe and Barnett 1997*a*; Pugin et al. 1999). The development of the moraine is thought to have occurred in four stages: I, subglacial sedimentation; II, subaqueous fan sedimentation; III, fan to delta sedimentation; IV, ice-marginal sedimentation.

The model traces the transition from subglacial to proglacial conditions during moraine formation and examines the order and timing of sedimentation. The event sequence recording the transition between erosional glaciofluvial events, expressed as channels found beneath the moraine, and glaciofluvial and glaciolacustrine sedimentation in coarse channel fills, fining-upward sequences, and fan and delta sedimentation that completed moraine building is incompletely understood. However, this event sequence affected ice and basin geometry, lake level and outlet stability, and the timing of events that concentrated a thick, raised, sediment package north of Lake Ontario (Fig. 2).

This paper integrates geomorphology, sedimentology, and surface mapping, subsurface geophysics, and borehole data interpretation to provide further understanding of the ORM. It emphasizes regional methodologies and three-dimensional techniques that are necessary to improve understanding of the ORM and similar moraines or complex glacial terrains (e.g., Eyles et al. 1985; Sharpe et al. 1992). Geomorphological analysis using a digital elevation model (DEM), air photographs, and satellite imagery of the moraine and surrounding area allows insight into regional relationships not readily apparent on topographic maps (e.g., Shaw et al. 1996). Detailed and regional mapping, combined with sedimentological mapping of exposed sediment and cores, provides information on composition, structure, and environments of deposition. Integrating these data with shallow geophysics (e.g., reflection seismic profiles) affords definition of seismic facies and subsurface geometry that can be linked to surface landforms. This integration leads to an improved landform event sequence for the ORM

Geological setting and background

The Oak Ridges Moraine forms a drainage divide of high sandy ground between Lake Ontario and Georgian Bay. It extends from the Niagara Escarpment to beyond Rice Lake for a total lateral extent of approximately 160 km (Fig. 2). The ORM has been defined in many ways in the past, based primarily on geomorphology and (or) the distribution of surface sediment (Table 1). It is often referred to as a complex feature of interlobate origin, although this is disputed by some (Gwyn and Cowan 1978).

The moraine and older sediments rest on gently dipping, Paleozoic strata situated along the margin of exposed Precambrian shield north of the moraine. The Niagara Escarpment, a prominent bedrock-controlled cuesta, forms the western margin of the ORM (Fig 2) and played a fundamental role in its formation. A channel system both across and along the escarpment (Fig. 3) provided corridors for ice-marginal drainage that probably controlled regional water levels as the moraine formed (Chapman 1985).

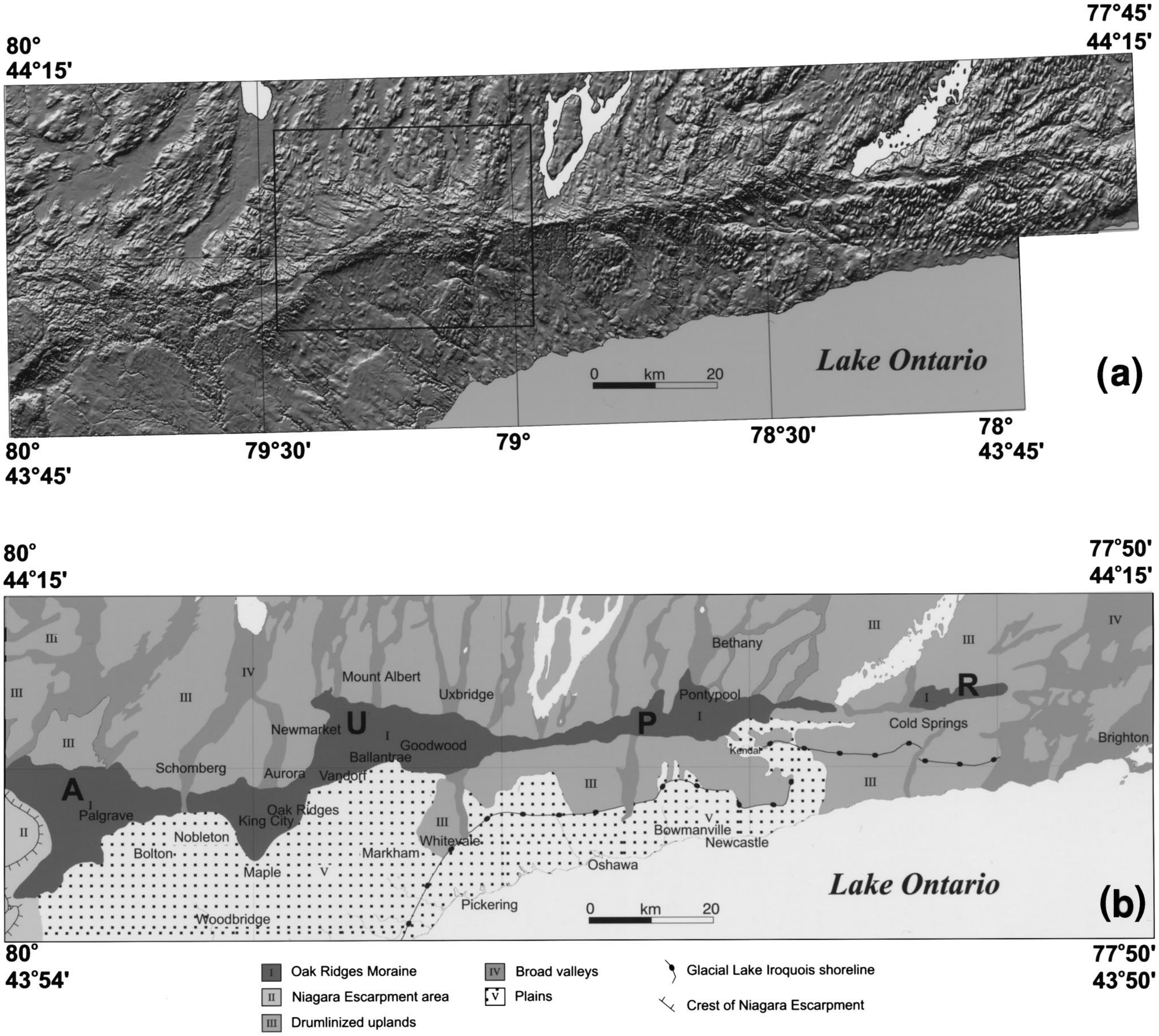
The ORM occurs in the southern marginal zone of the former Laurentide Ice Sheet (Shaw et al. 1996). To the north of the moraine is the Peterborough drumlin field (Chapman and Putnam 1943, 1951, 1984), which forms a regional northeast–southwest-oriented surface (Fig. 2) that is underlain by thick deposits of Newmarket Till. Several studies have suggested that the drumlin field underlies and extends beyond the ORM (Mirynech 1962; Gwyn and Cowan 1978; Barnett et al. 1991).

The drumlin field is cut by a complex, northeast–southwest-oriented, network of deep valleys (Fig. 4). The valleys have steep sides, a branching pattern, inset eskers, and large bedforms, and they cut adjacent strata. These features have been interpreted as tunnel channels formed by high-energy subglacial meltwater flow (e.g., Barnett 1989, 1990; Shaw and Gorrell 1991; Brennand and Shaw 1994). The ORM shares the channel landform association in common with the Valley Heads Moraine (Mullins and Hinchy 1989).

The channels appear to end at the ORM and thus they may be important to the origin of the moraine. This relationship needs to be assessed but it is only touched on briefly in this paper. Suffice it to say that channels are considered to relate to very large meltwater discharges (e.g., Barnett 1990), whereas the ORM has a significant component of fine-grained rhythmites, recording deposition in a glaciolacustrine environment (e.g., Gilbert 1997).

The south slope physiographic region, consisting of sloping land underlain by fine-grained sediments, is considered by some to contain part of the ORM (Chapman and Putnam 1984). Farther south, low-relief till and lake plains occur (Peel plains physiographic region of Chapman and Putnam 1984). These plains carry little evidence of regional channels except broad, shallow scours (Sharpe and Barnett 1997*a*), which are cut by the Lake Iroquois bluff (Coleman 1932). The Iroquois plain occupies the lowest land between the

Fig. 2. (*a*) Digital elevation model (DEM) of Oak Ridges Moraine (ORM), shown as a hill-shaded model (from Kenny 1997). Rectangle is the location of the area shown in Fig. 5. (*b*) Landscape elements of the ORM area visible on the DEM (from Skinner and Moore 1997).



Lake Iroquois bluff and Lake Ontario (Chapman and Putnam 1984).

Regional landscapes and sediment associations

Five main landscape elements can be observed from the analysis of enhanced topographic information displayed in a DEM of the study area (Fig. 2*a*; Kenny 1997; Skinner and Moore 1997). The five landscape elements, based on surface texture and elevation, are I, Oak Ridges Moraine; II, Niagara Escarpment; III, drumlinized uplands; IV, wide, flat-floored valleys; and V, areas of low-relief plains (Fig. 2*b*). The relationships of these five main landscape elements provide useful information for understanding the origin of the ORM.

These landscape elements generally have characteristic form and sedimentary associations. Using seismic reflection profiles and borehole data, the sediments, sedimentary architecture, and landform relationships can be extended into the subsurface (Pugin et.al. 1999). These are necessary techniques in areas where sediments are complex and their thickness can exceed 200 m.

The ORM contains extensive areas of hummocky topography, smaller areas of elevated plains, and narrow ridges that suggest various degrees of ice control during formation. The ORM consists of four large, elevated, wedge-shaped bodies (from west to east: Albion Hills (A); Uxbridge (U); Pontypool (P); and Rice Lake (R) sediment wedges, Sharpe et al. 1994*b*; Fig. 2*b*). These bodies are separated by narrower, east–west ridges. South of Rice Lake, the moraine is

Table 1. Development of ideas on extent and origin of Oak Ridges Moraine (ORM).

Author	Contribution
Bigsby (1829)	Noted “Oak Ridge,” the height-of-land, north of Toronto
Logan (1863)	Suggested moraine extended from Niagara Escarpment to east of Trent River
Taylor (1913)	Formally defined “Oak Ridges Moraine”; extended from King and Maple to the Trent River; inferred interlobate and overlapping nature (Lake Ontario Lobe, younger, and Lake Simcoe Lobe, older)
Chapman and Putnam (1943)	Modified Taylor’s definition of ORM; included smaller moraines named by Taylor extending the moraine to the Niagara Escarpment and to approximately Trent River (e.g., Logan 1863); agreed to interlobate origin (most accepted definition of ORM)
Gravernor (1957)	ORM interlobate and may be old and, in part, palimpsest, having been overridden by a readvance from the north
Mirynech (1962, 1978)	Eastern ORM moved west of Trent River (Castleton); ORM was not overridden
White (1975)	Redefined ORM in west based on sediment character; identified a separate Palgrave Moraine (Lake Ontario ice only); ORM to include only interlobate high-level sands in King Township
Gwyn (1972)	Sandy till underlies ORM north and south (Newmarket; Bowmanville Tills)
Gwyn and DiLabio (1973)	Palgrave Moraine extended to all areas on south flank of ORM covered by Halton Till
Duckworth (1975, 1979)	Palgrave Moraine extended into Newmarket area; ORM not interlobate; a braided stream deposit fed from the south
Gwyn and Cowan (1978)	ORM not an interlobate moraine; it is a young feature (~13 ka)
Chapman (1985)	Identified strong regional control on water level and sedimentation within ORM
Barnett (1992, 1993, 1994)	ORM is interlobate and composite (e.g., Taylor 1913); subaqueous fans, deltas, end moraines of both northern and southern ice lobes; one till, Late Wisconsinan, underlies ORM; linked tunnel valleys and ORM genesis
Gorrell and McCrae (1993)	ORM has subglacial origin in eastern area; ORM linked to eskers, tunnel channels
Brennand and Shaw (1994)	Early part of ORM was deposited in a subglacial depositional environment (esker)
Gilbert (1997)	ORM sediments at Vandorf formed in 100 m deep lake in about 100 years
This paper	ORM is not continuous along its length; has several depositional environments: subglacial, ice-marginal, and proglacial lacustrine; ORM comprises smaller landforms, including Palgrave Moraine; ORM origin is linked to channel filling; sedimentation was rapid, a few hundred years at most

absent, isolating the Rice Lake sediment wedge from the wedges farther to the west (Fig. 2).

On close examination of the DEM, combined with surface mapping, it is possible to recognize several smaller landforms or architectural elements within each sediment wedge (e.g., Barnett 1995, Fig. 5). For example, the Uxbridge sediment wedge (Fig. 5) contains the Bloomington and Holt fans, low-relief plains (Goodwood and Ballantrae plains–deltas), areas of hummocky topography (Palgrave moraine), and minor ridges (Uxbridge moraines). In addition, some smaller landforms (bedforms) occur within valleys leading directly into the moraine south of Rice Lake (Gorrell and Brennand 1997). The sediments of the ORM are discussed below.

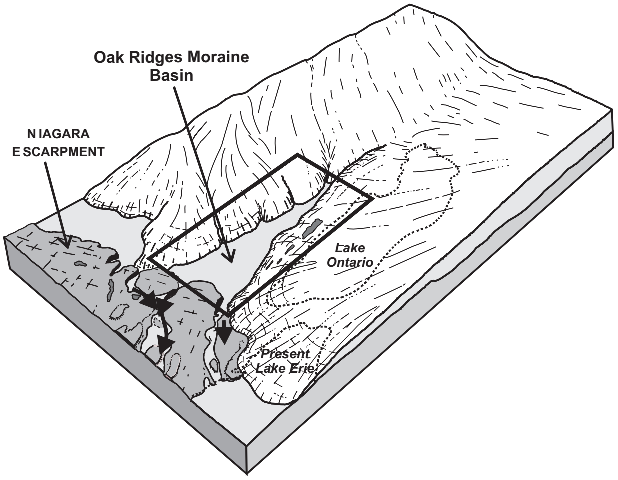
The Niagara Escarpment forms the western margin of the ORM (Fig. 2) and played a fundamental role in moraine formation. A channel system, eroded into the cuesta and along its face, provided corridors for meltwater to drain southwestward and northwestward as the ORM was forming (Fig. 3; Chapman and Putnam 1984; Hunter and Associates and Raven/Beck Environmental Ltd. 1996). These channels probably controlled regional water levels during moraine building (Chapman 1985).

The Caledon channel (White 1975) follows one of several reentrants in the escarpment face and is cut down to an elevation of about 425 m (Fig. 6). The channel cuts through the gravelly Singhampton and Paris moraines, west of the ORM, located above the Niagara Escarpment. Lower channels occur along the escarpment face at elevations of 350 m at Acton, approximately 290 m at Campbellville, and about 245 m near Kilbride (Fig. 6; Karrow 1989).

The channel network along the Niagara Escarpment has either bare bedrock floors or is floored with coarse gravel (Cowan and Sharpe 1973; Cowan 1976) that indicate high-volume southwesterly flows up to elevations of about 425 m. The Caledon channels contain outwash terraces of coarse, high-energy gravel facies (Costello and Walker 1972; Fraser 1982). All these channels acted as outlet controls for the trapped meltwater into which ORM sediments accumulated and hence they provide a water-level datum for the sedimentary depositional settings.

The landscape north of the moraine consists of large areas of uplands separated by wide, flat-floored valleys (Fig. 2). The upland surfaces are drumlinized and are considered to be part of the Peterborough drumlin field. Based on examination of the DEM and field mapping, the uplands are found

Fig. 3. Synoptic view from the southwest of ice positions and depositional environment in the Oak Ridges Moraine area. Study area is highlighted by the rectangle. Arrows indicate drainage atop the Niagara Escarpment. Drawing by J.R. Glew, Queen's University.



both north and south of the moraine (Fig. 2; Barnett 1997*b*). There is little change in drumlin long-axis orientation on either side of the moraine, and thus it appears that these surfaces extend beneath the moraine and were formed by a common process.

The drumlinized uplands are composed of a regionally extensive, dense, stony, sandy silt to silty sand diamicton, the Newmarket Till (Figs. 2 and 4; Gwyn and DiLabio 1973), which outcrops in drumlins both north and south of the moraine (Barnett et al. 1991). In drill cores obtained throughout the area, the Newmarket Till is intercepted between elevations of 200 and 280 m (Fig. 4) and has seismic velocities between 2 and 3 km/s, making it a useful marker horizon for the interpretation of seismic profiles (Pullan et al. 1994; Boyce et al. 1995). Seismic profiles from a survey run across ORM sediments show ridges on a thick, high-velocity facies (till in Fig. 7; Pugin et al. 1996) beneath ORM sediments. These ridges are similar to surface forms (drumlins) found north of the moraine. This confirms the idea that a regional till sheet and drumlin field continue beneath the ORM (Barnett et al. 1991; Sharpe et al. 1994*a*, 1996; Gerber and Howard 1996; contrary to Gravenor 1957; Boyce and Eyles 1991). The extension of both drumlins and Newmarket Till south of the moraine was also verified by drilling (Barnett 1993) and by mapping (e.g., Sharpe et al. 1997, Fig. 4).

Large, flat-floored, underfit valleys (tunnel channels), oriented northeast–southwest, dominate the landscape north of the moraine (Fig. 2). The channels are commonly 1–4 km wide, steep sided, up to 50 m deep, and they may contain eskers on their floors (e.g., Barnett and Dodge 1996). In places, the channels extend beneath the moraine and beyond to the low-relief plains south of the ORM. The extension of both uplands and channels beneath the ORM indicates that their formative processes were regional in scope. In the western part of the area, the channels contain thick sediment fills overlain by recent organic accumulations in wetlands. South of Rice Lake, a broad, steep-walled, east–west channel occurs along the axis of the ORM. It links the adjacent sediment wedges. The density of the channel network and its anabranching pattern separate them from narrower, incised postglacial valleys.

The network of large, wide, south-trending channels is also revealed to be up to 100 m deep beneath ORM sediments by drilling (Barnett 1993; Russell et al. 1998) and by reflection seismic profiles (Fig. 7; Pullan et al. 1994; Pugin et al. 1996). These profiles show an unconformity (erosional surface) defined by the steep-walled channels and upper drumlinized surface of the Newmarket Till (Fig. 7). The channel structures are the buried extensions of the tunnel channels observed north of the moraine (Barnett and Gwyn 1997; Fig. 2). In places, positive features at the base of the channel show an arched geometry that may be interpreted as eskers overlying gravelly fill (Sharpe et al. 1994*b*; Pugin et al. 1996).

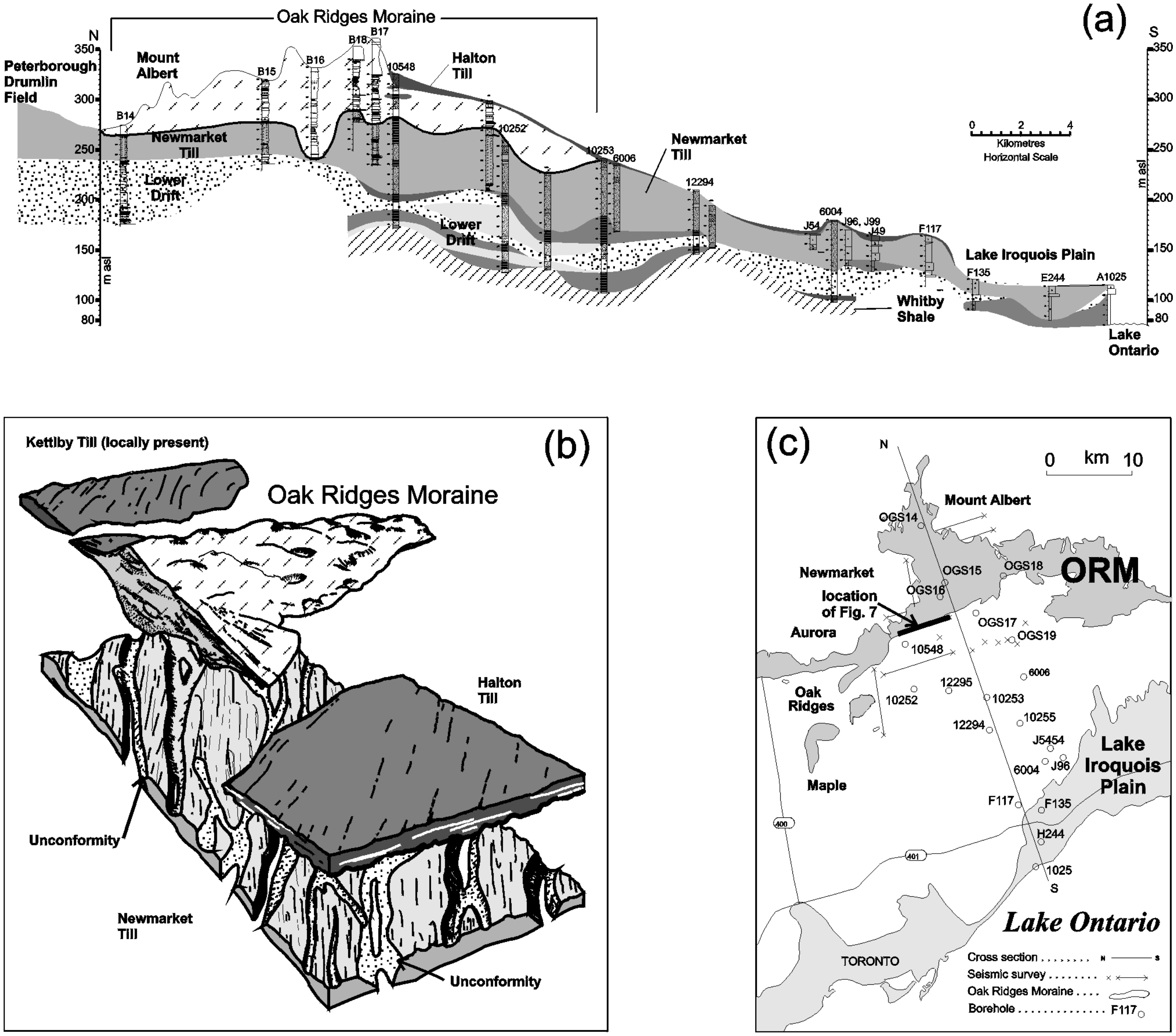
The age of the channel fills is not known and they may predate the moraine or they may be contemporaneous with it. Fining-upward sequences of gravel and sand are common in the tunnel channels near Rice Lake (Gorrell and Brennand 1997). Sheet gravels and large cross-sets (megaripples; Shaw and Gorrell 1991) have been recognized in section and on seismic profiles (Pugin et al. 1996, 1999). Streamlined bedforms also occur within the channels south of Rice Lake (Gorrell 1997).

The broad, low-relief plains bordering the southwestern margin of the ORM (Fig. 2) are, in part, subdued extensions of the wide, flat-floored channel and drumlin uplands and, in part, are covered by glaciolacustrine sediment (e.g., Sharpe and Barnett 1997*b*).

In summary, the ORM is built on a regional unconformity (erosional surface) consisting of the irregular, streamlined upper surface (drumlins) of the Newmarket Till in the broad upland areas and the base of the deep, wide, inter-upland valleys. The valleys with their inset subglacial landforms are interpreted as having formed by the erosion of upland sediments by large subglacial meltwater flood events (i.e., tunnel valleys or tunnel channels). It follows that the streamlined upland surface (drumlins) had also been eroded by subglacial meltwater (e.g., Shaw and Sharpe 1987). An alternative mechanism for the formation of the streamlined upland surface is erosion by subglacial deformation (Boyce and Eyles 1991). However, erosion by subglacial deformation does not explain the formation of the large valleys that form the remaining part of the regional unconformity nor the coarse gravel fill and very large bedforms that are commonly found within the valleys. In places, the ORM sediments completely mask this erosional surface. South of the moraine the erosional surface is partly subdued as a result of later sediment infilling.

The Niagara Escarpment forms the western margin of the ORM and played a significant role in moraine formation. The system of channels along the escarpment provided outlets for ice-marginal drainage and they controlled regional water levels during moraine building.

Fig. 4. Regional geology and stratigraphic architecture in (*a*) cross section and (*b*) block profile of the central part (*c*) of the Oak Ridges Moraine study area. Location of boreholes and seismic reflection profiles, including the profile displayed in Fig.7, are shown in (*c*).



Oak Ridges Moraine sediments

The Oak Ridges Moraine sediment wedges contain areas of hummocks, plains, and ridges. Their sediments include diamicton and predominately thick sets of fining-upward, rhythmically bedded, silt, sand, and gravel (Fig. 8) of glaciofluvial and glaciolacustrine origin, resting on an irregular channeled surface. The sediments formed within four main sedimentary settings: (*i*) subglacial, (*ii*) subaqueous fan, (*iii*) glaciofluvial delta, and (*iv*) ice-marginal environments. They also represent proximal (high energy) to distal (low energy) settings. Detailed sedimentological study of outcrops (Fig. 8) and drill core (Fig. 9) has helped reconstruction of the main depositional environments of the moraine (e.g., Barnett 1995).

The ORM in places reveals raised, coarse sediments arranged in a linear fashion with finer grained flanking sediments. The core of the Uxbridge wedge (Fig. 5: eskers at the north end of the Bloomington fan) contains sand and gravel bodies trending southwest and dominated by thick sequences of clast-supported, pebble to boulder gravels with poorly defined, southwest-dipping beds (Barnett 1994). Individual gravel beds may display normal or reverse grading. The core of the Pontypool wedge also contains coarse, clast-supported, gravelly sediments arranged as tabular sheets recording westward paleoflows (Barnett 1997*a*). These coarse sediments are believed to have been deposited in confined, ice-walled conditions, likely as open-channel eskers. Sharp-crested eskers in tunnel channels near Bethany (Fig. 2*b*; Barnett 1997*b*) may have provided sediment to the Pontypool wedge, or the eskers were deposited later.

The Rice Lake wedge also contains abundant coarse sediments in large bedforms (Fig. 8*a*). Megaripples are found within broad tunnel channels that lead into the ORM; the channels also contain eskers (e.g., Shaw and Gorrell 1991; Gorrell and Brennand 1997; Russell et al. 1998). Channel sheets grade (fine) upward from stratified gravels to thick sets of cross-laminated sands, and they may also merge with

Fig. 5. Landform elements of the Uxbridge sediment wedge of the Oak Ridges Moraine shown overlying a hill-shaded digital elevation model created by Kenny (1997). Explanation of text and symbols: Bf, Bloomington fan; bBf, buried Bloomington fan; Bp, Ballantrae plain; Gp, Goodwood plain; Hf, Holt fan; Pm, Palgrave moraine; Rd, Rosedale delta; Ud, Utica delta; Um, Uxbridge moraines. Moraines and lines with triangles attached (ice-contact slopes) mark former ice-marginal positions during wedge formation. For explanation of roman numerals see key in Fig. 2.

the moraine wedge. The channel fills also contain large (10–15 m) scours in sand (Gorrell and Brennand 1997). The scours are filled with diffusely bedded sands (Fig. 8*b*) that include rafts of underlying sediments. These sediments relate in part to high-flow channel sedimentation and in part to subglacial ice-controlled sedimentation within standing water. A similarity in bedforms and sediment style between the moraine and the channel fills indicates a potential link between channel-filling events and moraine formation.

Extensive, thick, tabular sequences of sand, silt, and minor gravel, which become fine and thin upwards, are common facies found in large buried sheets, fan-shaped bodies, and hummocks of the ORM (Barnett 1992; Paterson 1995; Sharpe et al. 1996; Paterson and Cheel 1997; Russell et al. 1998). Some of these sand or silt packages sit as raised hummocks between adjacent glaciofluvial channels (e.g., near Oak Ridges: Sharpe and Barnett 1997*b*). The large fan-shaped bodies record abrupt downflow transitions from proximal gravel sediments to thick (10–15 m) accumulations of climbing ripple-drift sands (Barnett 1994; Paterson and Cheel 1997). Proximal to mid fan facies contain numerous large, well-defined, and 10–20 m wide channels filled with decimetre-scale, sandy pebble–gravel, cross-beds, and larger, metre-scale, planar-tabular cross-beds. Some sands are laterally continuous (0.5–2 km; Fig. 7; Pugin et al. 1996), and dip gently to the southwest. They display horizontal bedding, planar-tabular, and trough cross-bedding. In places, they are cut by steep-walled channels filled with massive sands (Fig. 8*b*).

Distal to these sediments (and upwards in the ORM sequence) are thick, mainly fining-upward sequences of rhythmically bedded, fine sand and silt (Fig. 8*c*) that eventually grade to silt–clay couplets, varves deposited in a distal glaciolacustrine setting (e.g., Gilbert 1997). These sediments are revealed in boreholes (Fig. 9) from the westernmost part of the moraine, particularly beneath the Halton drift, and in related low-relief plains. They show that moraine sedimentation extended well south of the surface expression of the moraine (Maple, Fig. 2*b*) and, in places, extended to bedrock (Fig. 9*a*; Russell et al. 1998). Where erosion along tunnel valleys has completely removed the Newmarket Till and older sediments, ORM sediments reach thicknesses of about

150 m (Fig. 9*a*). In summary, widespread sequences indicate subaqueous fan depositional environments possibly up to 100 km^2.

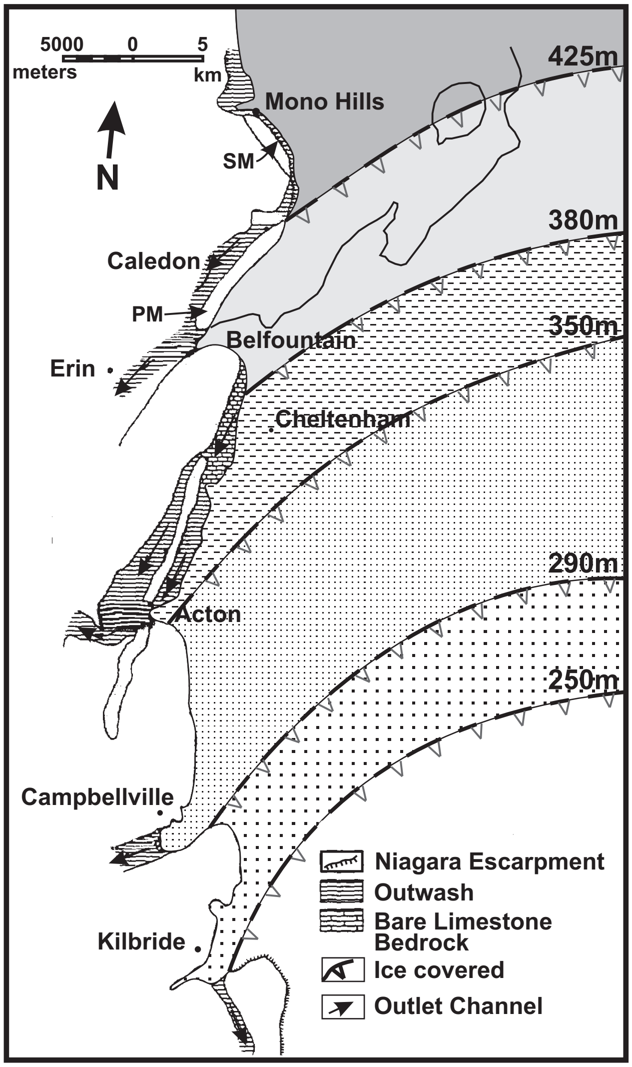
Regional landform relations, textural trends, and paleoflow measurements indicate flow to the southwest, west, northwest, and locally divergent flow directions (Duckworth 1975, 1979; Barnett 1994; Paterson 1995; Russell et al. 1998). The above sequences and flow patterns are well recorded and are interpreted as subaqueous fans (e.g., Bloomington fan, Fig. 5; Barnett 1994; Paterson and Cheel 1997), deposited rapidly in a lake ponded between the ice and the greater than 425 m high Niagara Escarpment (Figs. 3 and 6).

Sand plains with coarsening-upward sequences are found in several areas of the ORM (e.g., Ballantrae plain, Fig. 5; Barnett 1997*a*). A Geological Survey of Canada (GSC) borehole near Vandorf reveals 10–20 m of uniform, coarse to medium sand overlying (at ~285 m asl) many ten's of metres of rhythmically bedded, fine sand, silt, and clay (Fig. 9*b*). The top portion of these sediments is interpreted as deltaic deposits. The deltaic deposits overlie basinal (Gilbert 1997) and subaqueous fan deposits. Paleoflows in the delta package are predominately westward where it sits on the north flank of the ORM height of land (Figs. 2 and 5). A prominent break in slope on this surface appears to indicate a prograding wedge of deltaic sediment on the depositional slope (Fig 5; Barnett 1994). Delta sediments that flank the core of the Pontypool wedge show northerly paleoflows, deflected northward by the preexisting moraine core sediments (Barnett 1997*b*). Shoreline features related to these delta surfaces are mapped nearby (e.g., Barnett and McCrae 1996). Aeolian sand dunes, 5–8 m high, drape the delta top.

Falling water levels necessary to allow delta sedimentation resulted from the retreat of the ice dam at the Niagara Escarpment (Fig. 3), allowing successfully lower ice-marginal channels (e.g., Caledon outwash, Fig. 6) or subglacial conduits to open. The delta interpretation at Ballantrae is supported by the ice-controlled outlet channel identified at ~290 m asl at Campbellville (Karrow 1989). The Campbellville outlet projects to about 327 m asl, or about the surface of the Ballantrae plain (Fig 5; a remnant delta surface).

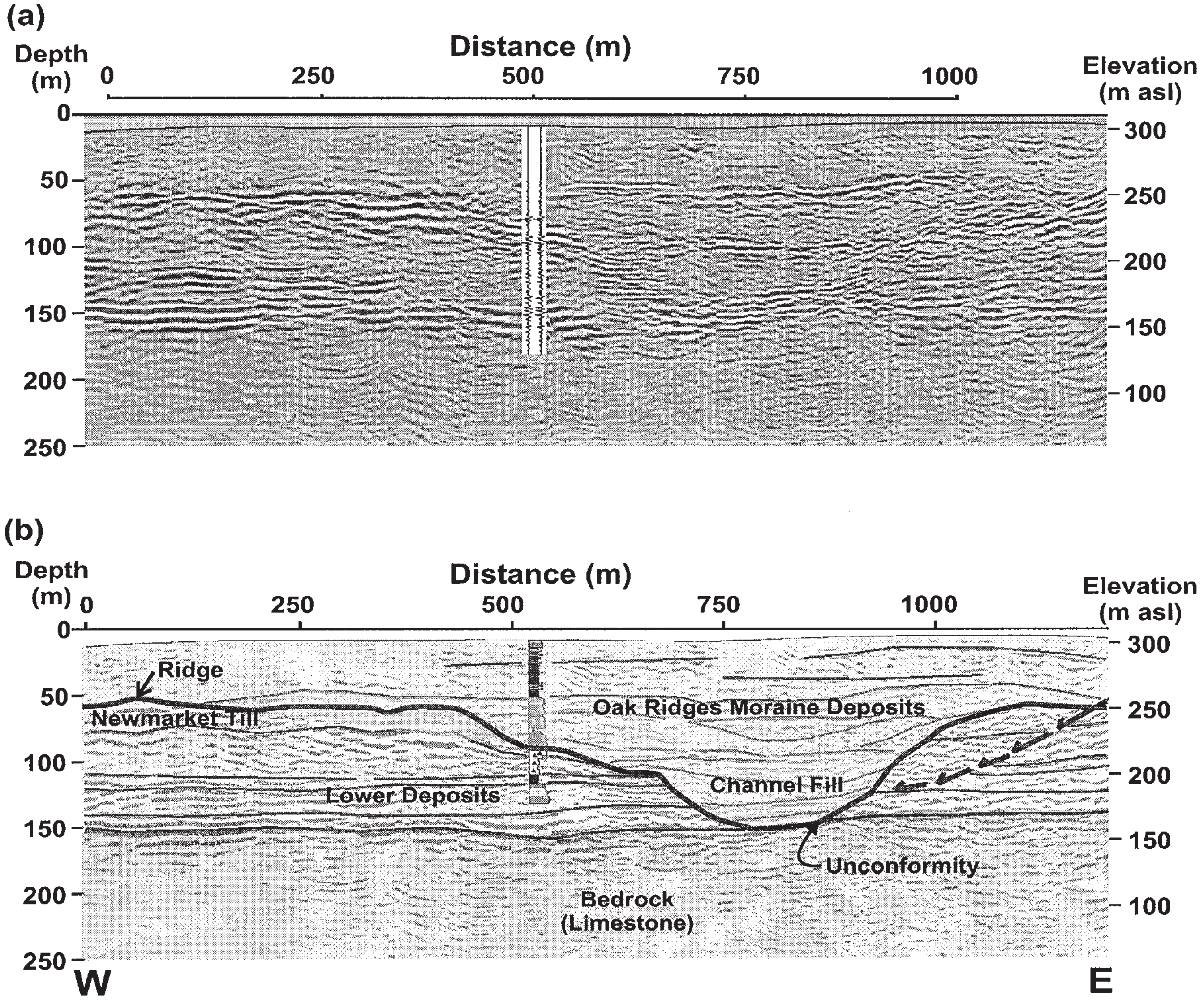
Ice-marginal sedimentation, whether subglacial or proglacial, refers here to late sedimentation where debris flow and low-energy sediments were better preserved than during periods of high-energy deposition of sand and gravel. Silty Halton Till and associated drift onlap the hummocky southern flank of the moraine (Fig. 4), particularly in the Humber watershed, where it may be more than 30 m thick (Russell and Arnott 1997). Thickness of this till diminishes sharply away from the ORM on broad low-relief plains east of the Humber watershed (Sharpe and Barnett 1997*a*). Thin, discontinuous fine-grained, glaciolacustrine sediments and interbedded beds and lenses of Halton Till (Fig. 8*d*) appear to indicate a facies gradation to the sediments of the adjacent low-relief plains, particularly in the area of glacial lake deposits north of Markham (e.g., Sharpe and Barnett 1997*b*). Halton drift consists of thicker diamicton deposits, up to 15 m thick, represented by the Palgrave ridge (moraine: White 1975). It commonly contains quasi-continuous silt, clay, and fine sand beds and lenses that are 0.5–2 m thick (Russell and Arnott 1997).

Fig. 6. Outlet channels and water level controls on Oak Ridges Moraine sedimentation along the Niagara Escarpment (after Chapman 1985). Singhampton Moraine (SM) and Paris Moraine (PM) are shown draping the Niagara Escarpment.



A modest Halton glacial advance (2–3 km) toward the north overrode the southern edge of the ORM fan and delta sediments (Barnett 1994). The advance may have extended farther in the Humber River watershed. The limit of the Halton advance is marked by a narrow zone of hummocky topography containing extensive kettle depressions (Palgrave moraine: White 1975) and by the surface distribution of the Halton Till (Fig. 4). Advance is indicated by the occurrence of unidirectional overturned strata beneath (Halton) diamicton, the orientation of shear planes within the diamicton, and the occurrence of lodgement till over melt-out till along the southern flank of the ORM (Barnett 1993). Local incorporation of subsole sediments into the base of the till was also noted locally. In addition, deposits of fine-grained rhythmites (30–50 cycles) between gravels beneath the Goodwood and Ballantrae plains may be the result of an advance of the Ontario basin ice, temporarily closing the Campbellville outlet.

Fig. 7. Portion of east–west seismic reflection profile acquired near Vandorf (Figs. 2 and 4*c*) showing (*a*) processed data (downhole velocity profile is superimposed) and (*b*) the interpretation (from Pugin et al.1999). Half arrows mark the base of a possible large slump along the buried valley wall. A 135 m deep lithologic log (inset) displays the geological material encountered. Triangle fill represents diamicton. See Fig. 9 caption for explanation of other units in graphic logs.



Rippled sands with northward paleoflow are associated with the Halton Till and indicate that the advancing ice margin also contributed meltwater flow to the ORM, north of Brampton (Saunderson and Jopling 1980), in the Humber River watershed (Russell and Arnott 1997), and near Bloomington. Meltwater pulses also contributed sand to Halton drift from the ORM complex, lying to the north and east. The strong glaciolacustrine character to the Halton drift, the high ponded water levels (greater than 335 m asl in the Uxbridge wedge area; Fig. 2), and the limited ice fluctuation suggest that ORM sedimentation was transitional to Halton drift and adjacent proglacial lake sedimentation (especially near Markham).

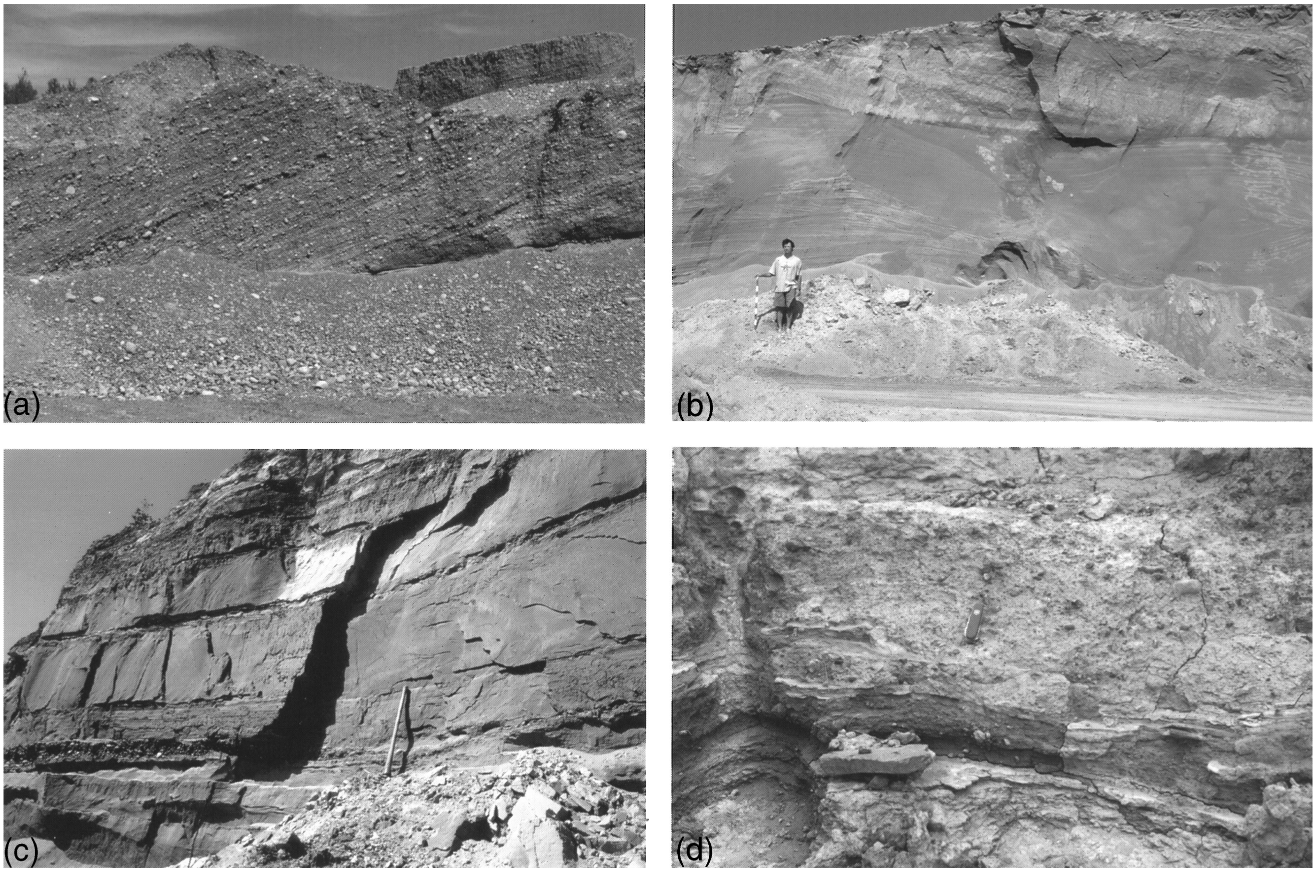
Model of moraine development

The Oak Ridges Moraine was built on a high-relief, erosional surface defined by the surface of the drumlinized uplands and network of deep tunnel channels. Moraine development is highlighted in four stages and evolved rapidly from a glaciofluvial-dominated core to flanking glaciolacustrine-dominated wedge sediments (Fig. 10). The model reflects the transition from subglacial to proglacial conditions during moraine formation, with emphasis on the main processes of deposition. It may reflect sedimentation patterns through time, although the “stages” are not necessarily sequential and reconstruction reflects an idealized sequence. The initial stages of moraine construction are better exposed in the east; in the west, these stages are buried by later stages.

Stage I: subglacial sedimentation

Stage I portrays the initial stage of moraine formation where sediment-laden meltwater was delivered along subglacial and possibly englacial openings to subglacial cavities

Fig. 8. Prominent lithofacies of the Oak Ridges Moraine. (*a*) Large-scale gravel cross-beds interpreted to result from a migrating bedform, Brighton; exposed face approximately 3m high. (*b*) Diffusely bedded sand with rip-up clasts, interpreted to result from deposition from suspension by hyperconcentrated flow (Gorrell and Shaw 1991; Brennand 1994), Bolton. (*c*) Sand and silt rhythmites, inferred to be glaciolacustrine deposits, Coppins Corners; grub hoe handle is 1 m, for scale. (*d*) Interbedded sand, silt, and diamicton, representing deposition from suspension and sediment flows, Woodbridge; knife is 10 cm long, for scale.



(Fig. 10, I). Initially, erosional processes produced channels (Nye channels), such as the east–west channel south of Rice Lake (Fig. 2). Early, formative flows may have also enhanced the network of north–south channels, or used the corridors for sediment delivery to the ORM. As flow waned, deposition of coarse to fine channel fills (Fig. 10, I) took place along the core of the ORM and beyond, as shown by the thick, coarse sediment sequences observed along channel bases in seismic profiles and borehole logs (Figs. 7 and 9).

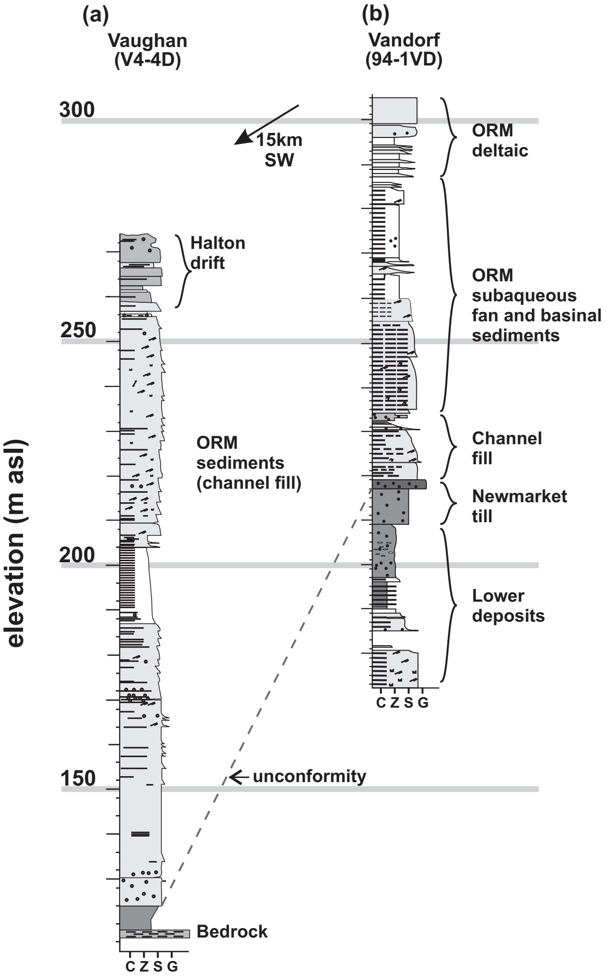
The channels north of the Rice Lake sediment wedge (Gorrell and Brennand 1997) contain coarse to fine sediment sequences that may be transitional to ORM sediments. The channels contain pendant bars and large ripples, similar to those associated with Missoula flood events (Bretz et al. 1956). The strata also contain high-energy scours (Fig. 8*b*) similar to those found in esker and proximal fan environments (Rust and Romanelli 1975; Gorrell and Shaw 1991; Brennand 1994; Brennand and Shaw 1994). Eskers found within these valleys tend to broaden to form gravel sheets and other bedforms (Fig. 10, I), where flow expanded to form a thick moraine segment (e.g., north of the Rice Lake wedge). Some long esker systems found well to the east of the ORM appear to connect to it (Gorrell 1997). These sedimentological data support the interpretation that the underfit valleys are tunnel channels eroded and filled by high-velocity, perhaps subglacial, meltwater.

The channel sediments and forms grade from gravels to sands and from sheets to large dunes as they near the ORM. Thus, there appears to be an intimate relationship between the channels, thick channel fills, eskers, and the moraine. The first stage, while fragmentary, is best observed in the Rice Lake sediment wedge, where an entirely subglacial origin is inferred (Gorrell and McCrae 1992).

Stage II: subaqueous fan sedimentation

The expansion of the subglacial cavity or expansion of a narrow ice-walled lake environment is highlighted in the second stage (Fig. 10, II). Proximal sedimentation was dominated by gravel; transition to sandy facies was abrupt and in many sites the high-energy gravelly sediments were buried. ORM sedimentary sequences (Paterson 1995; Paterson and Cheel 1997) are similar to those reported in other subaqueous fans (e.g., Rust and Romanelli 1975), although diffusely bedded sands are rare (Fig. 8*b*), and ice confinement resulted in proximal sedimentary facies extending farther, possibly 1–2 km, downflow. Distally (perhaps only 100–1000 m; possibly 1–5 km), cyclic, silt–sand ripple-drift sequences can dominate (Russell et al. 1998). Both the

Fig. 9. Graphic log of drill core from (*a*) Vaughan and (*b*) Vandorf. Figures 2 and 3 show sites. C, clay; Z, silt; S, sand; G, gravel. Parallel lines are rhythmites.



Pontypool and Uxbridge sediment wedges contain landforms and sediment sequences that illustrate this stage of moraine formation (Barnett 1994, 1995).

In the Uxbridge wedge, eskers lead into a large subaqueous fan from the northwest (Bloomington fan: Fig. 5) to form one of the highest parts of the moraine (>360 m asl). The fan sediments extend in a southwesterly direction as a linear body of plane-bedded sands and fine gravels (Fig. 10, II) cut by deep, broad, steep-walled scours, filled with massive sand, typical of fan environments. Distal deposits tend to have rhythmic fine-grained sets, indicating standing water. With outlet channels at the Niagara Escarpment at about 425, 380, and 350 m asl (Fig. 6), early ORM fan sedimentation could have occurred in water depths of over 100 m.

Stage III: fan to delta sedimentation

Stage III includes the transition of fan to fan delta and to deltaic sedimentation (Fig. 10, III), lateral to and overlying stage II, where ice-confined sedimentation occurs. Fan sedimentation in this stage is distal to primary sediment input sources and occurs in a large ice-controlled lake (Figs. 3 and 10, III). Fine sand and silt rhythmites were extensively deposited. These sets are the result of deposition primarily by underflows (Fig. 10, III) whose distribution is controlled by basin topography and source location. The rhythmically bedded sediments are thickest in the deeper parts of the basins (water depths 100–200 m) such as the preexisting troughs associated with the tunnel channels (Figs. 2 and 4). Distal fan sedimentation contributing to moraine formation is best preserved in the Humber River basin (Russell and White 1997) and the Albion Hills sediment wedge (Fig. 2*b*).

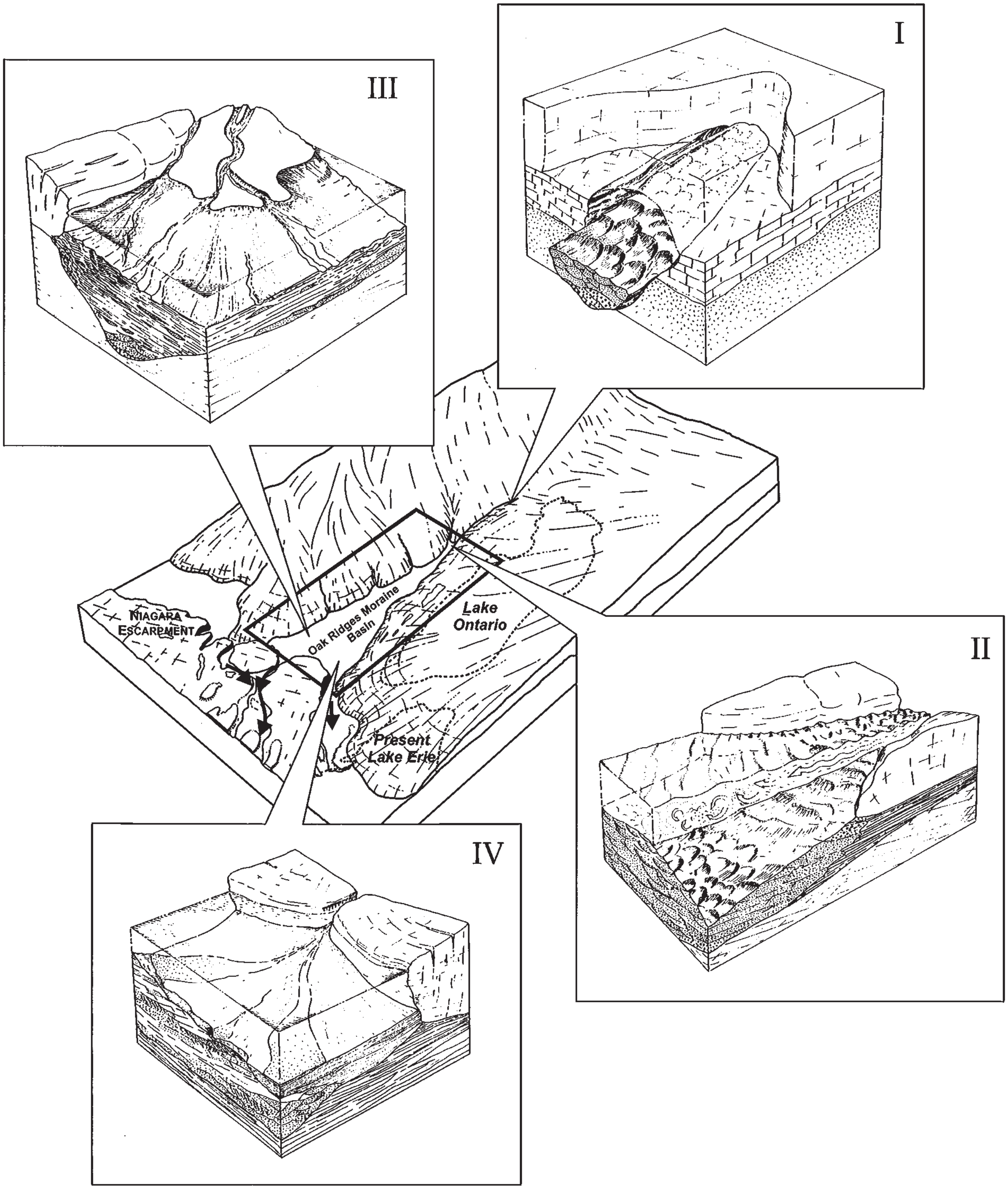
Glaciolacustrine fan sedimentation changed to deltaic sedimentation as regional water levels fell in response to the opening of the outlet at Campbellville on the Niagara Escarpment (290 m asl; Fig. 6). The lower outlet at Kilbride (245 m asl; Fig. 6) opened subsequently. Most of the Uxbridge wedge (Goodwood and Ballantrae plains: Fig. 5) is at an elevation of about 335 m and corresponds to a lake controlled by the Campbellville outlet. Allowing for isostatic rebound, the level of the proglacial lake projects to an elevation of about 327 m at Uxbridge.

Subaqueous fans were also built at localized input sources along the ice margins (e.g., Holt fan, 250–255 m asl: Fig. 5; Barnett 1994). Deltaic and glaciofluvial sediments were deposited in expanding glacial lake basins (Fig. 10, IV) formed between the receding ice margins and existing coarse moraine sediments (stages I and II). The landforms and sediments of the Pontypool and Uxbridge wedges illustrate this stage (Barnett 1994, 1995). Deltaic sedimentation dominated where sediment delivery was primarily by ice-marginal braided streams flowing westward to the expanding lake (e.g., near Ballantrae and Lake Scugog; Barnett 1997*b*; Fig. 10, III). The distribution of sediments was affected by rapid variation in discharge and outlet control (ice dam floatation and ice-marginal fluctuations) related to ice thickness and position. For example, silt–clay rhythmites occur within gravelly sediment sequences in the Goodwood area of the Uxbridge wedge (Duckworth 1979; Chapman 1985). These fine-grained rhythmites occur within sediments of the Ballantrae and Goodwood plains and were possibly deposited as the result of a rapid short-lived (30–50 years) rise in water level in response to the advance of the Halton ice (Barnett 1995). Data from a semicontinuous core of moraine sediments in the Uxbridge wedge, near Vandorf, indicate about 100 years of stable, deep-water lake sedimentation, delivered in a few main cylces (Gilbert 1997) prior to deposition of coarsening-up deltaic sands in the top 20 m of the core (285–305 m asl).

Stage IV: ice-marginal sedimentation

In the deeper basinal areas and along the southern flank of the ORM, the upper part of the succession of moraine sediments is commonly interbedded glaciolacustrine stratified sediments and massive to bedded diamictons (Halton Till and debris flows, Wildfield Complex, White 1975; Russell and Arnott 1997; Fig. 10, IV). Some of these sediments were deposited ice marginally, under a partially buoyant ice terminous or at a grounding line, particularly in the Humber River basin (Fig. 10, IV; Russell and Arnott 1997). In areas to the east, deposition predominantly focused along the glacial margin (Palgrave moraine, White 1975). The narrow part of the moraine south of Lake Scugog consists of a thick diamicton sequence, interpreted primarily as flowtills or glacially derived debris flows (Halton Till; Barnett 1994,

Fig. 10. Conceptual model showing the developmental stages of the Oak Ridges Moraine. I, subglacial sedimentation: high-energy erosion and coarse sedimentation within a tunnel; II, subaqueous fan sedimentation: ice-confined, high-energy to reduced-energy sedimentation of gravelly sequences transitional to large sandy sets; III, fan to delta sedimentation: distal fan deposition of silt–clay rhythmites and sandy subaerial braid-plain sedimentation; IV, ice-marginal sedimentation: debris flows, turbidity currents, and sedimentation from suspension. View is from the southwest. Drawings by J.R. Glew, Queen's University.



1997*a*). These sediments overlie subaqueous fan sediments deposited along the northern margin of the ice in the Lake Ontario basin. Evidence of northward-flowing conduits within the Lake Ontario basin has been presented by Saunderson (1975) and Saunderson and Jopling (1980).

Summary of moraine development

The four stages of moraine formation may be present in any one sediment wedge. In general, there is a transition from sub-glaciofluvial to glaciolacustrine and from subaqueous to subaerial environments of deposition. However, the importance and contribution of any one stage to the sediment wedge varies and is difficult to determine because deep sediments are incompletely exposed. The western sediment wedges (Albion Hills and Uxbridge; Fig. 2*b*) contains a more complete record of the four stages of moraine formation than the easternmost sediment wedge (Rice Lake). The ORM appears to have formed in a time sequence but more synchronous sedimentation may be revealed in deeper deposits.

Formation of the ORM

(1) ORM probably formed as the margin of the Late Wisconsinan ice melted back from atop the Niagara Escarpment. Initially subglacial conduits expanded to form a growing west-to-east reentrant between the main Laurentide Ice Sheet and a mass of ice in the Lake Ontario basin.

(2) ORM forms a thick sequence (up to 150 m) of stratified sediment deposited rapidly on a high-relief, regional erosional surface defined by a network of tunnel channels and the surface of the intervening drumlinized uplands.

(3) Coarse tunnel channel fills may show transitional relationships with the ORM in both landform sequences and sediment trends in boreholes.

(4) Lowest fills show north–south-trending paleoflows, whereas upper sediments have more axial (east–west) paleoflows.

(5) ORM sediments consist of heterogeneous to cross-bedded gravel, diffusely bedded to ripple cross-laminated sand, massive to rhythmically laminated silt and clay, and minor, massive to stratified diamictons.

(6) Moraine sedimentation was predominantly glaciofluvial–glaciolacustrine with late-stage diamicton accumulation along the ice margins.

(7) Moraine sediments were deposited, in part, in subglacial environments, but they were mainly deposited in ice-confined, subaqueous fan environments followed by deltaic environments of deposition. Varves within the moraine sediments indicate that wedge formation may have occurred in as little as a few hundred years.

(8) Sedimentation appears to have occurred generally in sequence from west to east at the four main sediment wedges, Albion, Uxbridge, Pontypool, and Rice Lake. However, more synchronous sedimentation may have occurred in the lowest beds.

(9) The Niagara Escarpment controlled water levels and hence moraine sedimentation as recorded by a series of outlet channels. For example, the Uxbridge wedge formed subaqueously until the outlet at Campbellville (290 m asl) was exposed; then subaerial and deltaic sedimentation occurred.

(10) The retreating ice margins shed ice-marginal diamictons into shallow lakes. An ice- marginal fluctuation of several kilometres deposited Halton drift during the final stages of moraine formation. Deposition of diamicton into shallow-lake environments may have occurred ice marginally, from beneath a partially bouyant ice terminus, or along the grounding line.

Conclusions

Integration of terrain evaluation methods increases our knowledge of large complex landforms (moraines). It can improve the understanding of the form, three-dimensional extent, and architecture present in complex features such as the Oak Ridges Moraine. The areal extent and interrelation of landform elements in the ORM and adjacent terrain are revealed in a high-resolution digital elevation model (DEM: Figs. 2 and 5) and in high-resolution subsurface data (e.g., seismic reflection profiles: Fig. 6).

The ORM was built on a high-relief erosional surface defined by deeply eroded tunnel channels and drumlinized uplands. Widespread glaciofluvial erosion preceded moraine formation as for other moraines, for example, the Valley Heads Moraine (Mullins and Hinchy 1989) and the Eagle–Finlayson, Hartman, and Lac Seule moraines in northwestern Ontario (Sharpe and Cowan 1991).

There is a transition from glaciofluvial to glaciolacustrine deposition. The ORM has a core of glaciofluvial-dominated sediments (subglacial cavity fills to confined subaqueous fans). These are overlain and flanked by slightly younger, topographically lower, glaciolacustrine sediments (deltas and basinal sediments). This landform–sediment relationship is present in the Harricana glaciofluvial complex (Brennand and Shaw 1996), stratified moraines in northwestern Ontario, and may be present in other stratified moraines, such as the Waterloo Moraine (Karrow and Paloschi 1996: Fig. 1). Glaciofluvial and glaciolacustrine sediments are predominant in these moraines even though diamicton may cover large surface areas, as it does in the ORM.

The location of the Oak Ridges Moraine may be related, in part, to its regional topographic setting, and this in turn affected the style of sedimentation. Major lake basins (Lake Ontario and Georgian Bay), the Niagara Escarpment, and the retreating ice front all combined to create deep, ice-marginal-lake conditions following the erosion of the tunnel channels. Water levels and sedimentation within the system were controlled at first by glacial hydrology and later by regional outlet channels (425–245 m asl) along the Niagara Escarpment. Water levels within the cavities or the expanding, ice-walled lake controlled sedimentation so that subaqueous deposition occurred prior to drainage through the Campbellville outlet, whereas subaerial and deltaic deposition occurred during and following the opening of the Campbellville outlet. Water levels fluctuated as a result of ice-marginal position, for example, with the Halton ice advance. However, generally a water level decline with time is recorded within the moraine sediments.

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