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Sharpe, D; Pugin, A; Pullan, S; Shaw, J

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Regional unconformities and the sedimentary architecture of the Oak Ridges Moraine area, southern Ontario[1]

David Sharpe, André Pugin, Susan Pullan, and John Shaw

Abstract: Seismic stratigraphy, geometry, and sediment facies within the Oak Ridges Moraine (ORM) area of Ontario record major structural elements and surfaces of the Quaternary sedimentary sequence. The derived stratigraphic architecture can be used to identify the key elements of a regional erosional surface, represented by an unconformity in the subsurface, and associated overlying channel sediments. The erosional surface – unconformity forms a distinct time datum in the Quaternary sequence, which provides an important aid to lithostratigraphic correlation. The architecture also gives improved understanding of the effects of erosion on the late-glacial landscape. The surfaces of erosional drumlins and intervening troughs, and the beds and banks of meltwater channels in the ORM area, define the regional unconformity, highlighted by seismic profiles linked to continuously cored boreholes. These features are attributed to regional-scale, subglacial meltwater flow events. The sculpted surfaces, which are analogous to water-eroded forms, the presence of boulder lags and coarse-grained deposits on the regional erosional surface, and the channels with undulating profiles provide the vital supporting evidence for a meltwater interpretation. The inter-regional extent of the unconformity is inferred from the coherence of regional paleoflows and the extent of drumlinized uplands, tunnel channels, and scoured bedrock terrain across ~75% of the landscape from the ORM area east and south to the Finger Lakes, New York. The implied magnitude of erosion suggests a pressing need for directed sedimentological study in those ocean basins that were probable depositional sites for flood deposits.

Résumé : La stratigraphie sismique, la géométrie et les faciès sédimentaires à l'intérieur de la région de la moraine de Oak Ridges (ORM) de l'Ontario enregistrent des surfaces et des éléments structuraux importants de la séquence sédimentaire quaternaire. L'architecture stratigraphique qui en découle peut être utilisée pour identifier les éléments clefs d'une surface d'érosion régionale, représentée par une discordance sous la surface et associée aux sédiments de chenal sus-jacents. La surface d'érosion–discordance forme une donnée de temps distincte dans la séquence quaternaire, ce qui aide grandement à effectuer la corrélation lithostratigraphique. L'architecture améliore aussi notre compréhension des effets de l'érosion sur le paysage tardi-glaciaire. Les surfaces des drumlins d'érosion et les fosses entre ceux-ci ainsi que les lits et les berges des chenaux de fonte des eaux dans la région de ORM définissent la discordance régionale, mise en évidence par des profils sismiques reliés à des forages carottés. Ces caractéristiques sont attribuées à des événements de fonte sous-glaciaire, d'échelle régionale. Les surfaces sculptées, qui sont analogues à des formes d'érosion aquatique, la présence de blocs résiduels et de dépôts à grains grossiers sur la surface d'érosion régionale, ainsi que les chenaux à profil ondulé fournissent des évidences essentielles qui soutiennent une interprétation d'eaux de fonte. L'étendue interrégionale de la discordance est déduite à partir de la cohérence des paléo-écoulements régionaux et de l'étendue des hautes terres à drumlins, les chenaux en tunnels et le socle affouillé sur ~ 75 % du paysage de ORM, vers l'est et le sud jusqu'aux Finger Lakes dans l'état de New York. La magnitude supposée de l'érosion suggère un besoin pressant pour une étude sédimentologique dirigée dans les bassins océaniques qui étaient probablement des sites de déposition pour les dépôts de crues.

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D. Sharpe[2] and S. Pullan. Geological Survey of Canada, 601 Booth Street Ottawa, ON K1A 0E8, Canada.
A. Pugin.[3] Institut F.A. Forel, University of Geneva, Rte de Suisse 10, Versoix 1290, Switzerland.
J. Shaw. Department of Earth and Atmospheric Science, University of Alberta, Edmonton, AB T6G 2E3, Canada.

[1] Geological Survey of Canada Contribution 200030.
[2] Corresponding author (e-mail: dsharpe@nrcan.gc.ca).
[3] Present address: Illinois State Geological Survey 615 E. Peabody Dr., Champaign, IL 61820, U.S.A.

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Introduction

Seismic surveys are used to identify the stratigraphic architecture of offshore and onshore Quaternary sequences (e.g., Mullins and Hinchey 1989; Lysa and Voren 1997; Pugin et al. 1999). Such architecture results from erosional and depositional events. Our understanding of sedimentary processes operating at a regional scale depends on understanding such erosional and depositional events at this scale (Lysa and Vorren 1997; Mullins and Hinchey 1989; Syvitski et al. 1997). In some cases, the nature of glaciogenic processes and the style of ice-sheet dynamics have been inferred from high-resolution marine (Cai et al. 1997) and lacustrine (Eyles et al. 1991; Mullins et al. 1996) seismic records, but without the advantage of controlling outcrop or borehole observation. In fact, most seismic surveys have little or no such control, especially those in marine settings (e.g., Davies and Austin 1997; Anderson et al. 2001; Novak and Stoker 2001), and only a few studies clearly link seismic facies and observed lithofacies (Vanderburgh and Roberts 1996; Pugin et al. 1999). Our purpose here is to interpret seismic sequences and sediment facies that are clearly defined in borehole records. We aim to refine our understanding of regional-scale processes by demonstrating the existence of extensive erosional surfaces and unconformities. Regional-scale erosional events relating to these unconformities and erosional surfaces appear to have scoured the Oak Ridges Moraine (ORM) area, Ontario and the region around the Finger Lakes (FL), New York. This conclusion is based on seismic architecture, supported by geological and geomorphologic mapping, continuously cored boreholes, and integrated models of subglacial processes.

A regional hypothesis

Shaw and Gilbert (1990) attempted to explain regional landform distributions and associated flow events in the eastern Great Lakes by way of a then contentious hypothesis. They suggested that two closely timed, subglacial meltwater floods, the Algonquin and Ontario events, produced regional unconformities and erosional surfaces (e.g., Shaw et al. 1998). Theoretical support for this hypothesis was provided by Shoemaker (1999) who predicted flow patterns for outburst floods in lake basins that closely match flow patterns indicated by drumlins in the Lake Ontario basin. Mapped landform relationships and analysis of event sequences using seismic data presented here offer a comprehensive test of the outburst flood hypothesis. We review the concept of subglacial flooding by citing a number of field studies from across the eastern Great Lakes region. These sites have variable levels of documentation, thus key features from well-studied sites are shown on a set of schematic illustrations to re-construct expected landform trends along generalized, formative flow lines. These critical landform relationships are linked by regional geological mapping to extensive subsurface data collected in the ORM study and correlated to the Finger Lakes region, New York.

We present evidence to identify a late-glacial unconformity across the eastern Great Lakes. This erosional unconformity cuts into preexisting glacial sediment and is characterized by water-scoured bedrock tracts, upland drumlin fields, extensive boulder lags, and tunnel channel networks. It underlies gravel in channel fills that fine upwards to sand and silt. This evidence poses formidable difficulties for, or directly contradicts alternative explanations for, the unconformity and the landscape in the study area. These alternatives are (*i*) erosion during ice sheet instability and surging (Shoemaker 1992); (*ii*) erosion and deposition by subglacial deformation processes (Boyce and Eyles 1991, 2000); and (*iii*) channel erosion and fill by jökulhlaups and drumlin field formation by subglacial deformation (Mullins et al. 1996).

Geological setting

The eastern Great Lakes area (Fig. 1) straddles a portion of the Michigan Basin south of the Canadian Shield and west of the Appalachian Mountains (Fig. 1). The Niagara Escarpment, which crosses the area near the basin margin, is a cuesta formed in differentially eroded Paleozoic carbonate and shale–sandstone strata (Fig. 1). In general, thick (10–200 m) glacial sediment continuously covers the sedimentary basin (e.g., Brennand et al. 1998), whereas thin (< 5 m), sporadic sediment covers shield terrain. Some Paleozoic terrain has little sediment cover (e.g., Manitoulan Island, Bruce Peninsula; Barnett et al. 1991; eastern Lake Ontario area; Muller and Caldwell 1986). Quaternary studies of the region rarely highlight erosional surfaces or regional unconformities (Martini and Brookfield 1995), although a fluvial-weathered surface identified at a few localities by warm-climate fossil beds and believed to date from the last interglacial, is an exception (Karrow and Occhietti 1989).

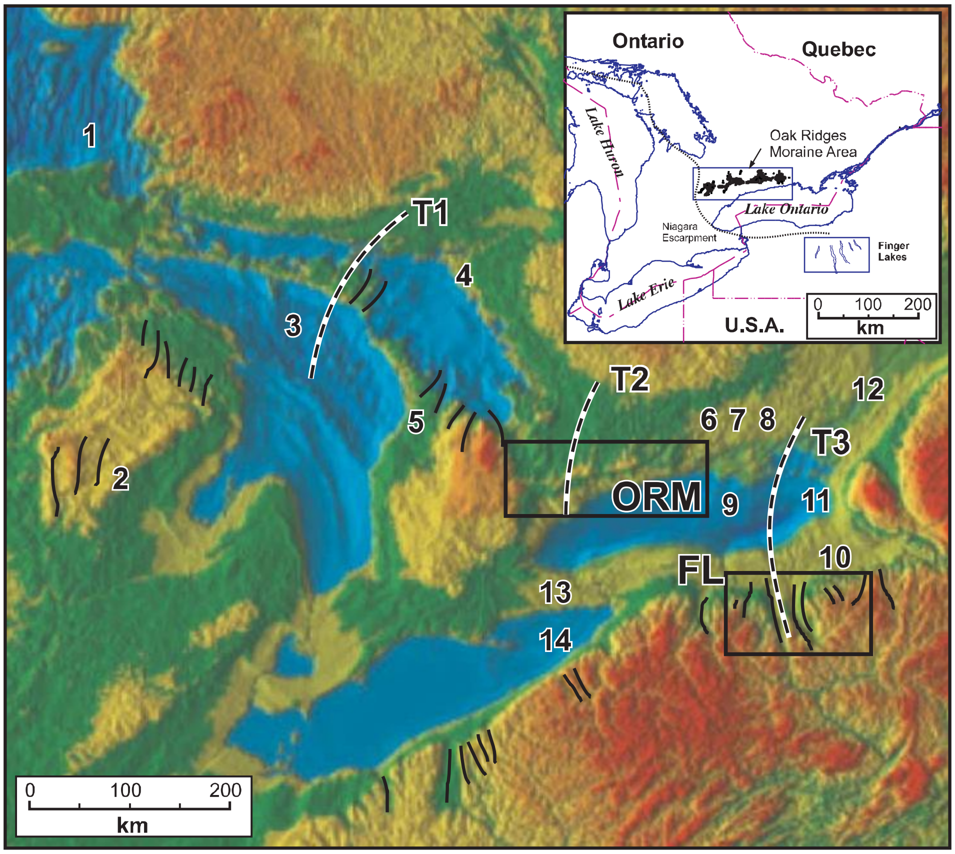
Regional landform architecture of Oak Ridges Moraine and Finger Lakes sediments

Southeastern Ontario and northern New York State are part of a varied eastern Great Lakes glaciated landscape showing numerous erosional landforms (Fig. 2). Eroded re-entrant valleys on the up-flow face of escarpments (e.g., Gilbert and Shaw 1994) run parallel to lake-bottom troughs (channels?) in northern Lake Huron, Lake Michigan, and eastern Lake Superior (Figs. 1, T1, Fig. 2, T1D). Scoured bedrock surfaces and channels contain sculpted forms (s-forms), including rock drumlins and flutings, and carry boulder lags near French River (Kor et al. 1991), across the Bruce Peninsula (Kor and Cowell 1998) and on the floors of Lake Erie (Lewis et al. 1999) and Georgian Bay (Blasco 2001) (Figs. 1 and 2, T1, T2). Low scarp noses adjacent to deep, sinuous rock channels, s-forms eroded into rock, and drumlins eroded into sediments comprise an erosional terrain in eastern Ontario (Shaw 1988; Shaw and Gilbert 1990; Gilbert and Shaw 1994; Gilbert 1994, 2000), on the floor of Lake Ontario (Gilbert 1990; Lewis et al. 1997; 2003) and in adjacent New York State (Pair 1997; Figs. 1 and 2, T3). In areas with thick sediment, drumlins are commonly sculpted from sandy till (Shaw and Sharpe 1987), and a network of tunnel channels is incised ~150 m into this till and older sediment (Barnett 1990; Brennand and Shaw 1994; Barnett et al. 1998; Russell 2001). The resulting erosional terrain contains extensive unconformities and regional-scale erosional surfaces in both the ORM (Fig. 2, T2) and FL areas (Fig. 2, T3).

Oak Ridges Moraine area

A > 100 m-thick, glaciofluvial–glaciolacustrine sediment complex extends eastward from the Niagara Escarpment and along the axis of the ORM located north of Lake Ontario

Fig. 1. Location of Oak Ridges Moraine (ORM) and Finger Lakes (FL) areas (rectangles) on digital terrain model (DTM; Gareau and Lewis in press). The Great Lakes DTM highlights several erosional terrains or areas of documented regional-scale surface erosion: Troughs (channels?) in the eastern Lake Superior (1; Patterson et al. 2003) and north-central Michigan (2; Fisher and Taylor 2002); scoured terrain in eastern Lake Huron (3; Blasco 2001); sculptured bedrock, rock drumlins, and boulder lags, French River (4; Kor et al. 1991) and Bruce Peninsula (5; Kor and Cowell 1998). Erosional sediment drumlins and tunnel channels east of ORM (6; Shaw and Sharpe 1987; Brennand and Shaw 1994); sculpted bedrock in eastern Ontario (7; Gilbert 1994); Wilton Creek (8; Shaw 1988); eastern Lake Ontario (9; Gilbert 1990; Gilbert and Shaw 1992; Lewis et al. 1996, 1997); Finger Lakes (10; Mullins et al. 1989); Upper New York (11; Pair 1997); St. Lawrence River (12; Bernard 1971); Niagara Peninsula (13; Tinkler and Stenson 1992); Lake Erie (14; Lewis et al. 1999). Dashed lines locate landscape transects (T1, T2, T3) shown in Fig. 2. Short black lines represent inferred channels and (or) reentrants in up-flow-facing escarpments.



(Fig. 3*a*) (Barnett et al. 1998). The complex was deposited between ~13 and 15 ka (Barnett 1992) and is superimposed on uplands with drumlins eroded into Late Wisconsinan till. The drumlinized till uplands are, in turn, dissected by an extensive network of tunnel channels (Fig. 3*a*; Barnett et al. 1998; Russell et al. 2003*b*). A conceptual geological model (Fig. 3*b*) provides a morpho-stratigraphic framework for the ORM area that was developed by integrating systematic landform and sediment mapping (Fig. 3*a*; Sharpe et al. 1997) with detailed seismic profiling and continuous-core drilling (Figs. 3*a*, 4; Russell et al. 1998; Pugin et al. 1999). The ORM model identifies four depositional units and two unconformities (Fig. 3*a*), all of which have inter-regional significance. Previous correlations of sedimentary units in the area used local mapping, site-scale seismic data on till plains, and sparse borehole geophysical logs (Karrow 1967; Fligg and Rodrigues 1983; Eyles et al. 1985; Boyce et al. 1995) with little regional architectural context. The new seismic and continuously cored borehole data include 50 line-km of strategically located seismic profiles (Fig. 3*a*; Pugin et al. 1999) controlled with > 25 continuously cored boreholes (e.g., Sharpe et al. 2003*a*; Fig. 4*d*) linked to detailed, region-wide, geological mapping (Fig. 3*a*). This integrated research allowed widespread erosion surfaces suggested earlier (Lewis and Sly 1971; Shaw and Sharpe 1987; Shaw and Gilbert 1990; Martini and Brookfield 1995; Shaw et al. 1998) to be correlated across and beyond the region.

Finger Lakes area

The Finger Lakes region (FL) straddles a series of escarpments south of Lake Ontario (Fig. 1). The area is marked by fields of north–south-oriented drumlins that are dissected by meltwater channels (e.g., Montezuma channels, Petruccione et al. 1996). Thick, stratified sediments partially fill the FL channels (Wellner et al. 1996), and the Valley Heads moraine to the south consists of thick sequences of glaciofluvial sediments (Muller and Caldwell 1986). These channel and moraine sediments were deposited in Late Wisconsinan time

Fig. 2. Three landscape transects (T1, T2, T3; see Fig. 1 for location) oriented along the inferred flow line of Late Wisconsinan flow summarize terrain features related to the proposed regional unconformity. T1, Georgian Bay transect traverses Canadian Shield (A, B) southwest across the Niagara Escarpment (C) to eroded sediment on Paleozoic strata in Lake Huron (D); T2, Lake Simcoe-Oak Ridge Moraine transect traverses Canadian Shield – Paleozoic escarpment terrain (A) to thick eroded sediment (B, C, D, overlain by ORM sediment (C); note ORM sediment has been partially removed to reveal the drumlin–channel surface; T3, Eastern Ontario – Finger Lakes transect traverses Canadian Shield – Paleozoic eroded terrain (A), Lake Ontario lake bed (B), rock and sediment (C), and eroded terrain in the Finger Lakes region (D). tc, tunnel channel; rd, rock drumlin; sd, sediment drumlin; en, escarpment nose; sf, s-form.

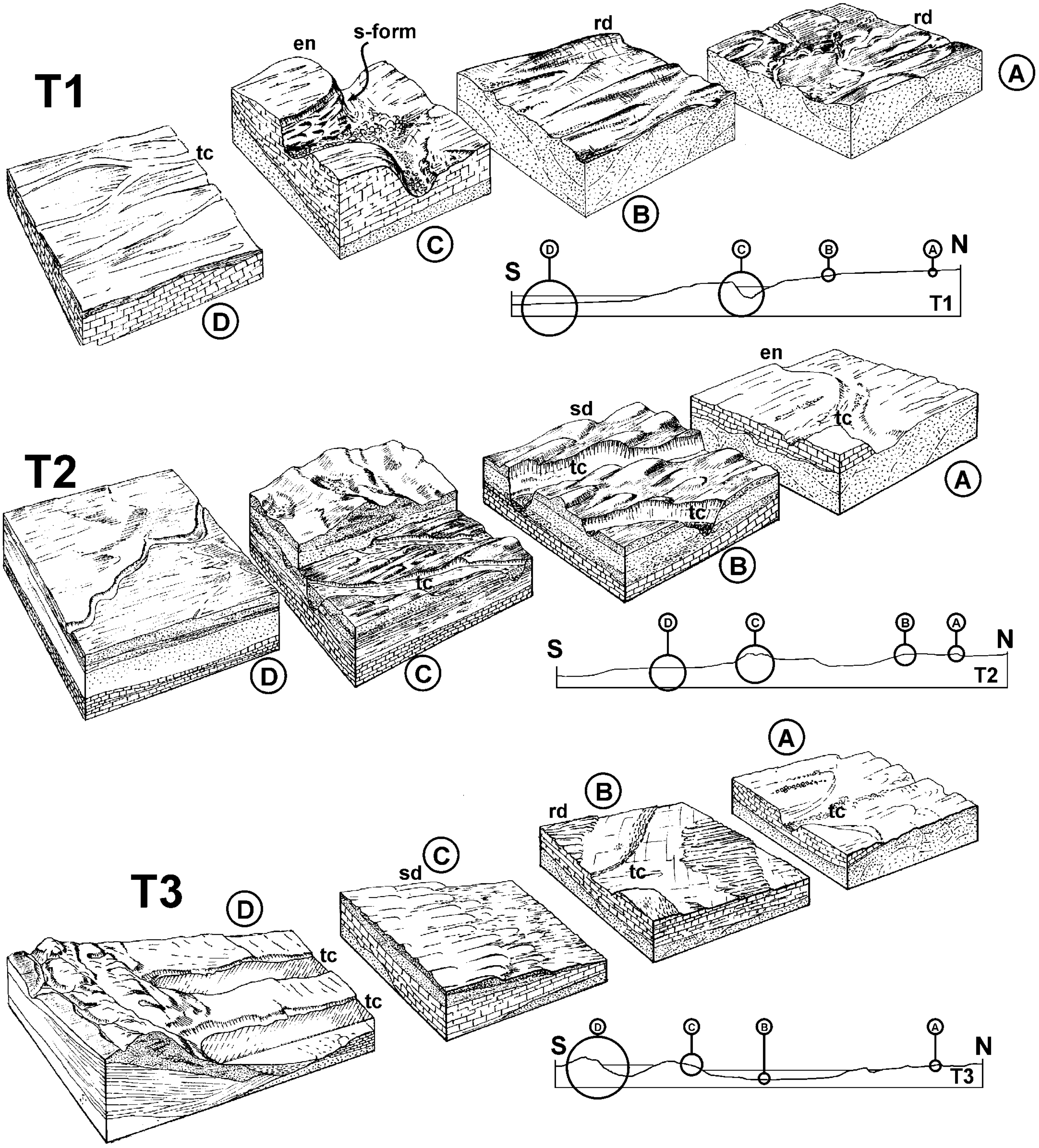
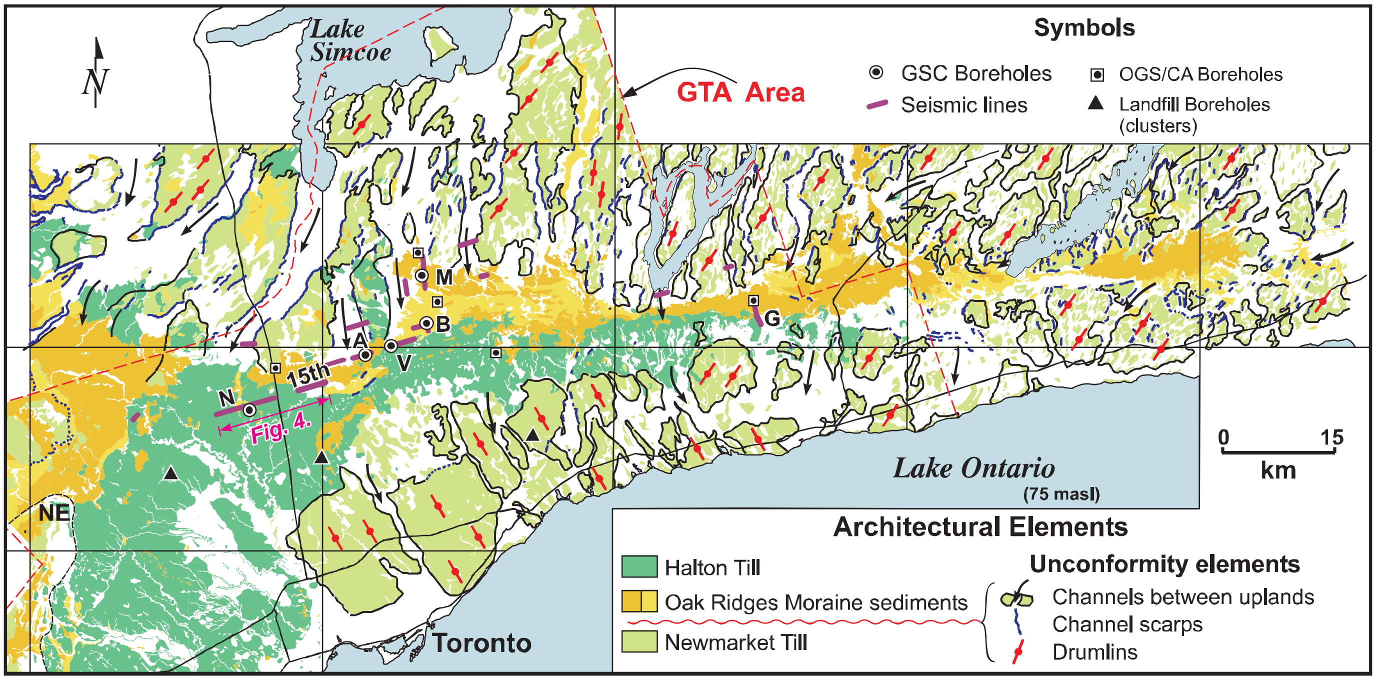


Fig. 3. (*a*) Terrain architectural elements and location of seismic lines displayed across the ORM study area. Most drumlins occur on the surface of Newmarket Till. Boreholes are located as single wells (GSC (Geological Survey of Canada), OGS (Ontario Geological Survey)) or as clusters at landfill sites with ~10–20 boreholes per site. NE, Niagara Escarpment. Seismic lines: A, Aurora; B, Ballantrae; G, Grasshopper Road; N, Nobleton; 15th, 15th Side road; V, Vandorf Side road.



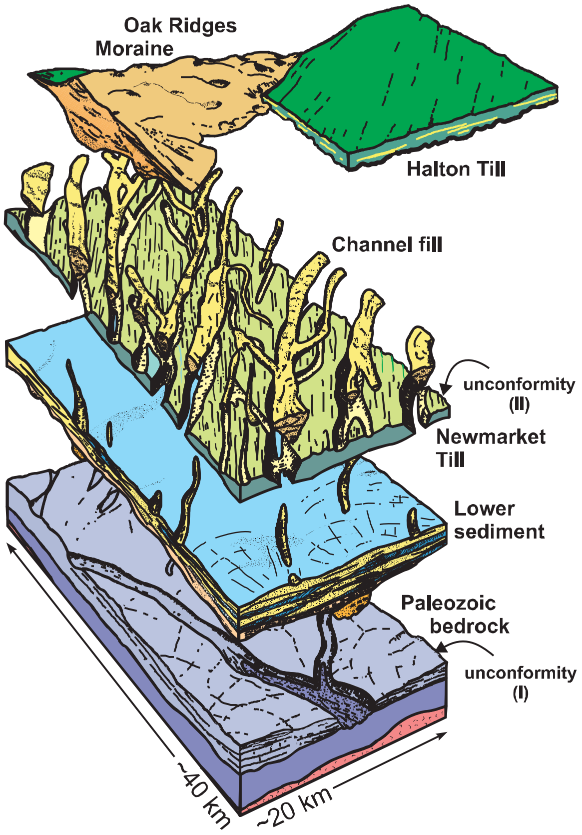
between ~13.9 and 14.5 ka based on basal peat dates and are correlated to marine, meltwater isotope "spikes" dated ~13.5–14.5 ka (Mullins et al. 1996).

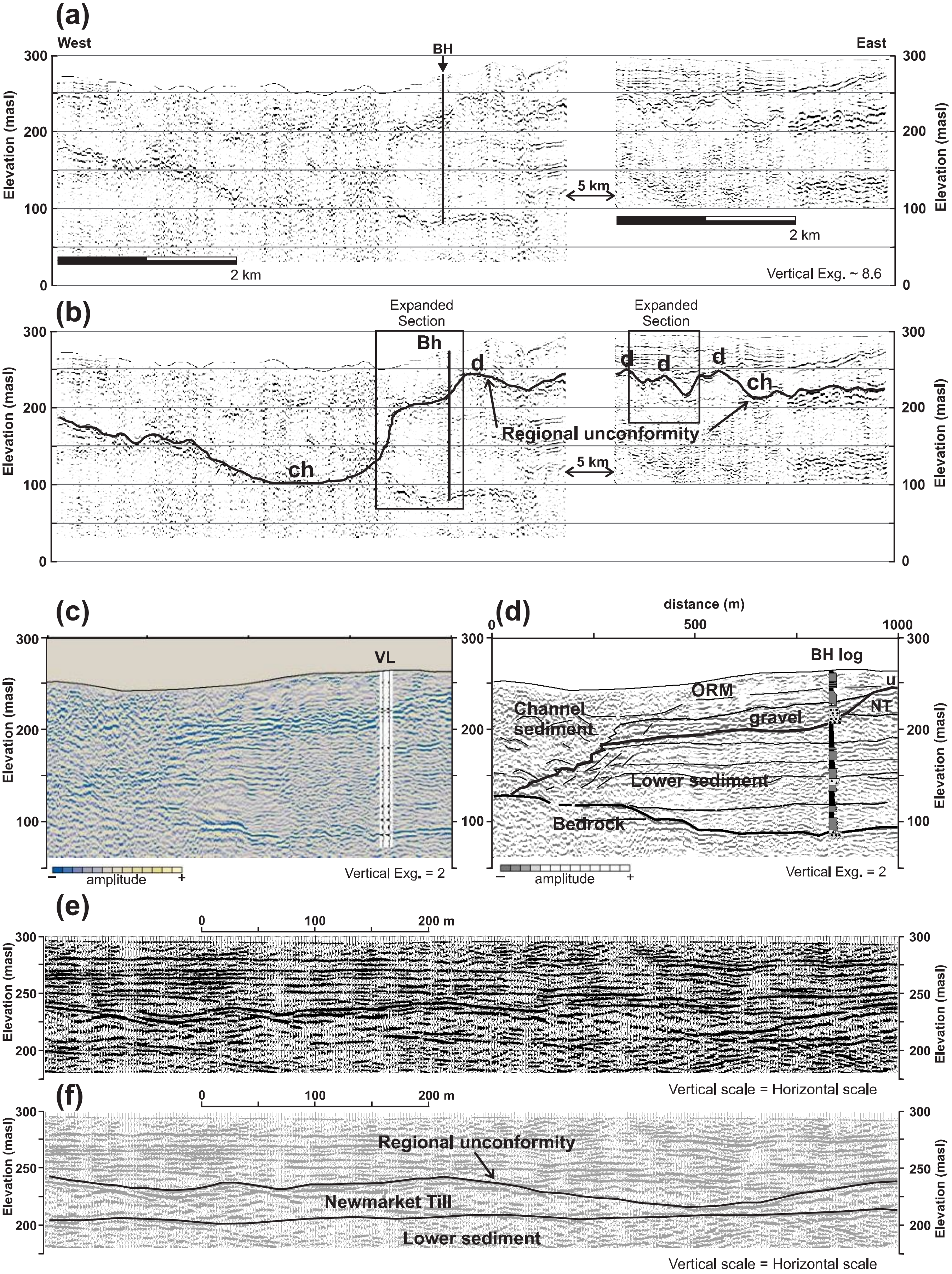
Late Wisconsinan unconformity

A prominent discontinuity is observed over ~50 line-km of ORM seismic profiles (Fig. 3*a*). The discontinuity in sedimentary sequences appears as a well-defined reflector on seismic sections (Figs. 4, 5*a*). Correlation with boreholes and sedimentary exposures clearly show the reflectors marking the contact between (*i*) Newmarket Till and older deposits, including bedrock, and (*ii*) overlying channel fill and ORM stratified sediment. The reflector traces the surfaces of buried drumlins and the floors and sides of tunnel channels. It also crosscuts tabular sedimentary strata, including local striated boulder pavements and sandy lenses within exposed Newmarket Till (Sharpe et al. 1998; Boyce and Eyles 2000). The till is evidently older than this discontinuity. Strong reflectors at the eroded upper surface of the Newmarket Till most clearly illustrate the discontinuity (Fig. 4*a*; Pugin et al. 1999). Weak reflectors indicate areas where the Newmarket Till is missing and ORM sediment rests directly on stratified deposits that predate the till (Fig. 4*b*).

This well-documented discontinuity is an erosional unconformity, which amalgamates with older unconformities at bedrock surfaces (Fig. 4*b*). The unconformity can be traced at surface and in the subsurface over the ~10 000 km^2 of the ORM area. An essential point for regional correlation is that the erosional surface includes drumlinized till upland surfaces and bedrock surfaces with s-forms found to the north (Fig. 2). The unconformity also includes the floors and sides of tunnel channels dissecting these broad surfaces (Figs. 4–6; Barnett

Fig. 3 (concluded). (*b*) Conceptual geologic model of ORM area, consisting of 6 major packages: Paleozoic bedrock, lower (pre-Late Wisconsinan) sediment, Newmarket Till, channel sediment, ORM sediment, overlying Halton Till.




(a)
West
East
BH
Elevation (masl)
300
200
100
0
5 km
2 km
2 km
Vertical Exg. ~ 8.6
(b)
Expanded Section
Expanded Section
Bh
d
d
d
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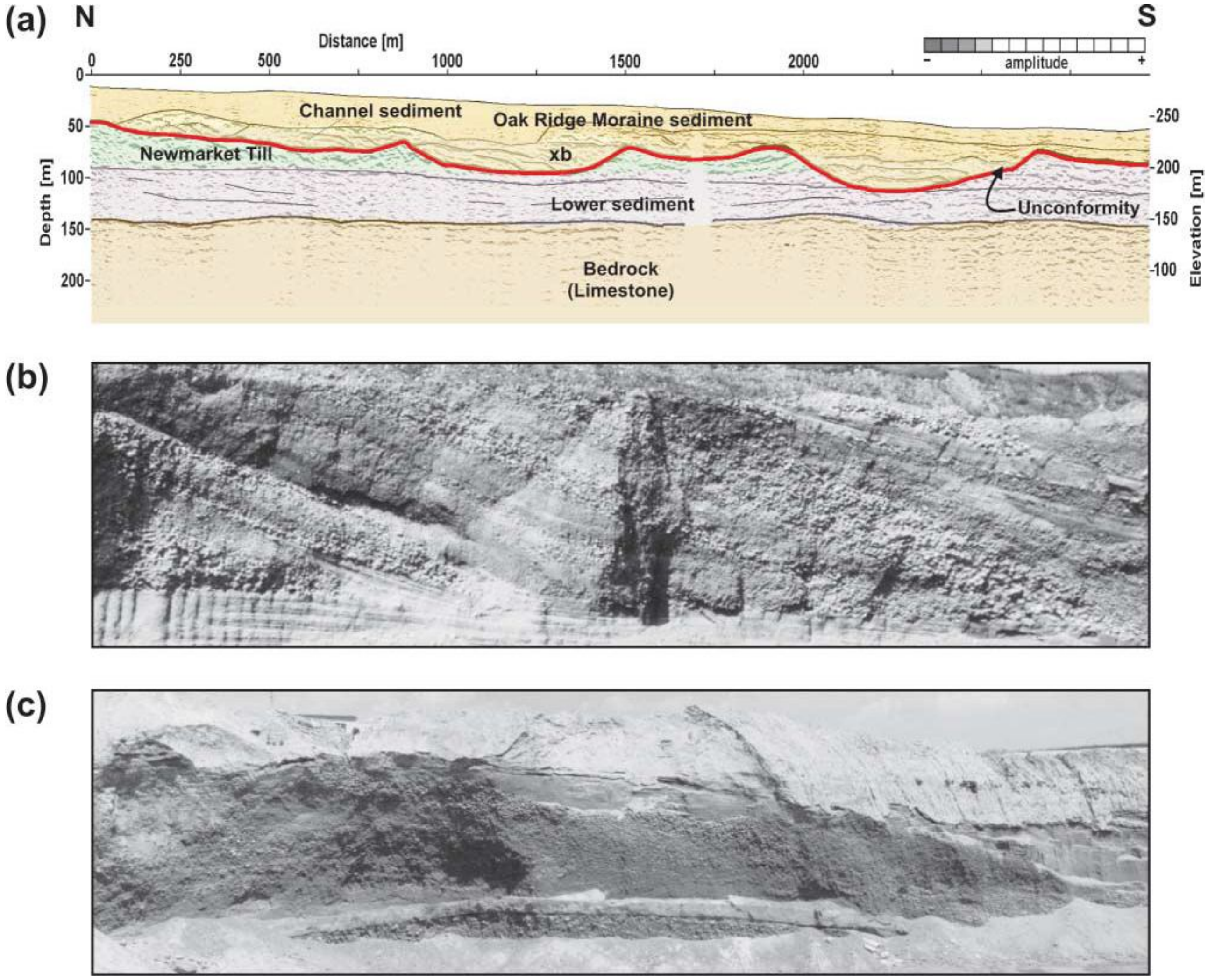
ch
Regional unconformity
5 km
(c)
VL
amplitude
Vertical Exg. = 2
(d)
distance (m)
0
500
1000
BH log
ORM
u
NT
gravel
Channel sediment
Lower sediment
Bedrock
amplitude
Vertical Exg. = 2
(e)
0
100
200 m
250
Vertical scale = Horizontal scale
(f)
Regional unconformity
Newmarket Till
Lower sediment
Vertical scale = Horizontal scale

Fig. 4. High-resolution reflection seismic profiles: (*a*) East–west seismic profile (~8 km of section) near Nobleton shows geometry of major reflectors and position of borehole (BH). masl, metres above sea level. (*b*) Interpretation (stratigraphic architecture) of (*a*) showing prominent high-amplitude reflectors that allow definition of a regional unconformity. Note that the sediment unconformity consists of drumlins (d) and channels (ch). Location of two expanded panels (c–d and e–f) is shown. Vertical exaggeration (VE) = 8.6. (*c*) Higher-resolution display of part of seismic section showing location of ~192 m deep borehole. High-amplitude inflections in velocity log (VL) identify key breaks in lithology. (*d*) Interpretation of (*c*) shows bedrock as a deep, high-amplitude reflector; parallel reflectors record bedding within Lower sediment. These beds are truncated by the regional unconformity (u) and filled with channel deposits. Hummocky reflectors on the unconformity are gravel as confirmed by a continuously cored borehole (BH log). NT, Newmarket Till; ORM, Oak Ridges Moraine sediment. VE = 2. (*e*) Higher resolution display of acquired seismic data with no vertical exaggeration. (*f*) Prominent reflectors interpreted as top of Newmarket Till record a drumlinized surface. The base of the till shows an approximately planar reflector overlying Lower sediment. Semi-parallel reflectors indicate ORM sediments above the regional unconformity.

Fig. 5. (*a*) North–south seismic profile and interpreted architecture recorded along Grasshopper Road. (*b*) Large (~10 m high) cross-beds (xb) of sandy gravel are found in tunnel channel sediment exposed in the area and inferred to occur in the area of inclined reflectors along Grasshopper Road seismic profile. Recent drilling confirmed gravel in this facies. (*c*) Dome-shaped structure exposed as ~15 m-thick glaciofluvial sand and gravel in a tunnel channel, is inferred to be recorded in a hummocky seismic facies (Fig. 5*a*; Pugin et al. 1999). These features are suggested to indicate the migration of bedforms (Brennand and Shaw 1994).

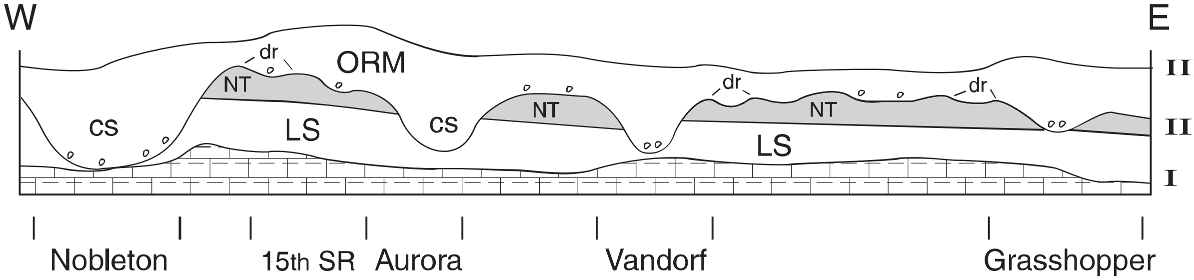


et al. 1998). The continuity of the unconformity is best illustrated by the seismic and borehole data at Nobleton (Fig. 4*d*), where a deep tunnel channel is contiguous with the floors of shallow channels and the surfaces of drumlins to the east (Fig. 6). The regional landscape unconformity encompasses a total relief > 150 m and the drumlin upland – channel terrain covers 75% of the area mapped in Fig. 3*a*.

Channels and dissected drumlin uplands

Large channels in the unconformity are 1–5 km wide and

Fig. 6. Schematic regional seismic architecture of the ORM area. The section portrays ~20–50 km of terrain, generalized from five seismic profiles (Nobleton, 15th Side road; Aurora, Vandorf–Ballantrae, and Grasshopper road; Pugin et al. 1999) and regional mapping (Sharpe et al. 1997). I, bedrock unconformity; II, Late Wisconsinan unconformity; III, modern surface; cs, channel sediment; LS, lower sediment; NT, Newmarket Till; dr, drumlin; open circle, gravel lag. Section is ~200 m thick. Each profile, except the 15th Side road, has an accompanying, continuously cored borehole (Sharpe et al. 2003*a*).



up to 150 m deep (Fig. 4*b*). Smaller channels cut into the Newmarket Till are up to 1 km wide and ~25–50 m deep (Figs. 4*a*, 4*b*; Pugin et al. 1999; Russell et al. 2003*b*). The truncation of parallel seismic reflectors indicates that large channels cut completely through the Newmarket Till into older bedded strata (Figs. 4*b*, 4*d*). North–south seismic lines show undulating 200–300 m long channel profiles with longitudinal scours inset into the Newmarket Till and underlying sediment (Fig. 5*a*; Pugin et al. 1999; Sharpe et al. 2003*b*). Barnett and Mate (1998) described coarse lags on the floors of exposed channels. Further, Shaw and Gorrell (1991) reported large-scale gravel bed forms (e.g., Fig. 5*b*) in a tunnel channel down flow from a reach floored by a boulder lag. Also, a database query of >> 10 000 borehole records across the region showed that gravel was predominant in the first 5 m above the unconformity (Logan et al. 2001; Russell and Sharpe 2002).

Drumlins, mainly cut in till, occur on the same Late Wisconsinan erosion surface as the ORM channels (Figs. 4*b*, 5*a*). These drumlins are either on inter-channel uplands (Fig. 4*b*) with scattered lags or within large channels that contain coarse sediment (Barnett 1990; Gorrell and Brennand 1997). Stone lags are common on Newmarket Till drumlins where gravel content is high (~10%) on this regionally consistent and distinctive till (Sharpe et al. 1997). Drumlin orientation on Newmarket Till varies but in general follows a NE–SW trend north of the ORM and a NW–SE trend south of the moraine (Fig. 3*b*). Crosscutting trends between drumlin fields (Fig. 3*a*) are considered to illustrate stages in the formation of the regional unconformity and mark the rapid reorganization of drainage and flow paths, estimated to be a matter of weeks to months (Shaw and Gilbert 1990; Shoemaker 1992, 1999). Channels that crosscut the drumlins (Fig. 3) most probably indicate that the channel-forming stage continued after drumlin formation had ceased.

Regional extent across southeastern Ontario

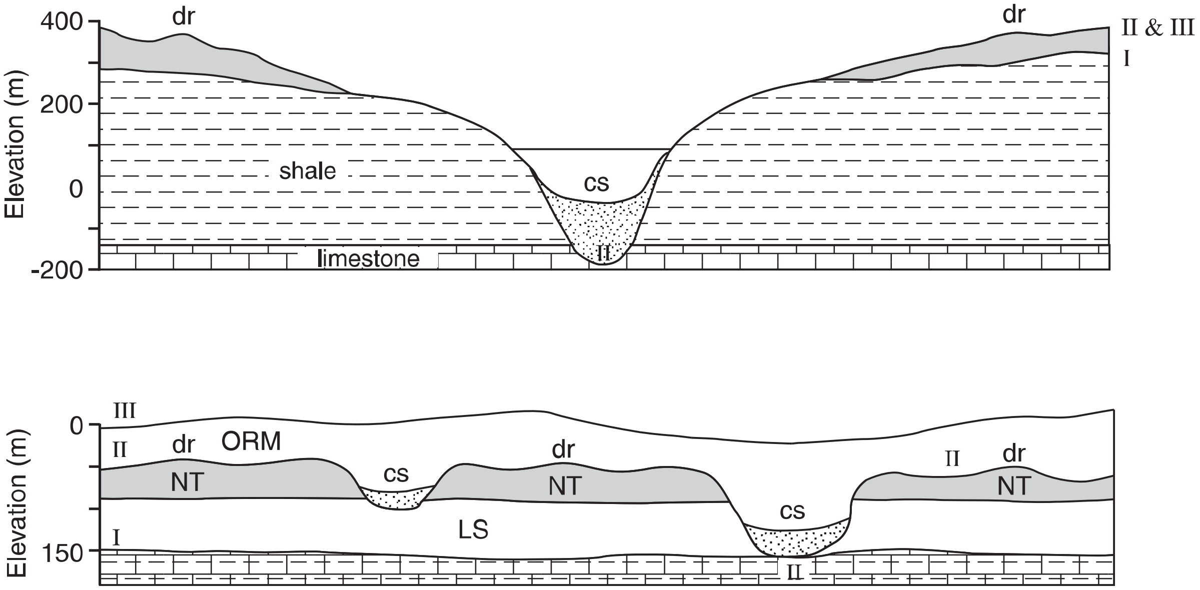
A drumlinized upland–channel landscape similar to the buried landscape in the ORM area exists across southeastern Ontario (Fig. 2, T3; Barnett et al. 1991). Eroded till plains, scoured bedrock, and channels are common between the ORM and the Quebec border (e.g., Gilbert 1994; Gilbert and Shaw 1994). Northeast from Kingston towards the Ottawa Valley, drumlins define a broad north-northeast to southwest flow path (e.g., Barnett et al. 1991). North of the ORM, drumlins in sediment and rock (Fig. 2, T1, T2; Gwyn and DiLabio 1973; Kor et al. 1991; Barnett and Mate 1998) within the same NE–SW-trending flow field show that the drumlin-forming flow was dominantly erosional. Scoured bedrock surfaces are ornamented with a variety of s-forms, including rock drumlins, over a broad range of scales. This indicates the action of turbulent flow with vortices varying in style and scale (Sharpe and Shaw 1989; Gilbert 1994, 2000; Shaw 1996). The sediment- and rock-eroded landscapes are commonly overlain by scattered boulders lags, some with percussion marks caused by impact during inferred saltation transport (Sharpe and Shaw 1987; Kor et al. 1991; Kor and Cowell 1998). Large-scale gravel bed forms also testify to powerful flows (Shaw and Gorrell 1991; Figs. 5*a*, 5*b*).

The regional sediment–bedrock unconformity is also correlated from land to the bottom of modern lakes (e.g., Gilbert 1990; Lewis et al. 1999; Blasco 2001). For example, drumlins and channels have been eroded into sediment and bedrock, both up-flow (Lake Simcoe, Todd and Lewis 1993; Todd et al. 2003; Pugin et al. 2001) and down flow (Lake Ontario, Lewis et al. 1996; Niagara Peninsula; Tinkler and Stenson 1992) of the ORM area (Fig. 2, T2). And using sonar profiles, Gilbert (2000) links scoured bedrock surfaces containing s-forms to deep sinuous channels in adjacent lakes in eastern Ontario.

Finger Lakes features

Terrain features in the FL area are similar to those in the ORM area and eastern Ontario. Drumlinized till uplands and channels mapped in the FL area (Muller and Caldwell 1986) also form part of a regional unconformity with buried elements detected by seismic surveys and borehole data (Fig. 7*a*; Petruccione et al. 1996). Channels, cut into drumlin fields, are deeply incised into thick till and bedrock (Fig. 7*a*; Mullins and Hinchey 1989). To the north, seismic profiles and drilling of the Montezuma tunnel channels and drumlins demonstrate that coarse gravel was deposited on this regional unconformity (Petruccione et al. 1996). A similar drumlin upland and bedrock-floored channel landscape to the northeast (Pair 1997; Bernard 1971; Fig. 1) shows widespread evidence of s-forms and noses on rock scarps that parallel the regional flow indicated by drumlins. In addition, we have observed widespread boulder lags on this landscape. Thus, evidence for a regional erosional surface in the Lake Ontario region applies equally to the FL

Fig. 7. Comparison of stratigraphic geometries: (*a*) Finger Lakes and (*b*) ORM across an ~10–20 km transect. I, bedrock unconformity; II, Late Wisconsinan unconformity; III, modern surface. ORM, Oak Ridges Moraine sediment; cs, channel sediment; NT, Newmarket Till; LS, lower sediment; dr, drumlin. Grey tone indicates regional till sheet.



area and points to event-sequences that may correlate with the ORM and eastern Ontario (Figs. 1, 7).

ORM and FL seismic facies and sediments above the regional unconformity

Oak Ridges Moraine

Seismic facies above the regional unconformity show similar event sequences for both the ORM and FL area sediments. Undulations in channel elevation along the Grasshopper Road seismic line (Fig. 5*a*) suggest subglacial erosion by pressurized flow. Coarse, glaciofluvial gravel forms the basal units in channels (e.g., Fig 4*d*; Pugin et al. 1999). This gravel is recovered from continuous cores and marks the first stage of infilling following channel erosion (e.g., Sharpe et al. 2003*b*). The seismic records of these gravels indicate coarse sediment with large-scale cross-stratification (Fig. 5*b*). The cross-stratification records glaciofluvial gravel dunes deposited in a deep, high-energy flow (Shaw and Gorrell 1991).

Hummocky reflectors with medium to low amplitude represent a facies with trough, lenticular, and onlapping geometries (Fig. 4*d*). Cross-stratified beds are associated with the hummocky architecture (Fig. 5*a*), which is probably developed in sand and gravel. Gravel > 15 m thick was encountered during drilling into this seismic facies at Nobleton (Fig. 4*d*; Pugin et al. 1999; Russell et al. 2000). Similarly, 25 m of gravel were encountered in drillcore recorded within hummocky seismic facies at Grasshopper Road (Sharpe et al. 2003*b*). The origin of these buried gravels is similar to gravel occupying nearby surface channels (Fig. 5*b*). The hummocky architecture in sands and gravels (Fig. 5*c*) may have resulted from internal waves related to vertical density gradients in a highly concentrated flow. Such hummocks are inferred to mark the existence of in-phase sediment waves on the channel bed (Brennand 1994).

Wall-terminating stratification at high levels indicates rapid deposition in the upper, fining-upwards parts of channel fills (Fig. 4*d*; Pugin et al. 1999; Russell et al. 2003*a*). The coarse channel sediments are conformably overlain by low-amplitude, weak to continuous reflectors (Figs. 4*e*, 4*f*). On the basis of borehole records, these tabular reflectors represent vertical accretion of sand and silt under low-energy flow conditions. Ripple bedding and parallel-laminated graded bedding support the interpretation that deposition of the upper sediments was under relatively low-energy conditions.

Finger Lakes area

Mullins et al. (1996) described similar sediments to those of the ORM on the regional unconformity of the FL troughs. Their data from 1300 line-km of ship-track, single channel, reflection profiles and direct sedimentary information from a 120 m-deep borehole show distinctive characteristics for the FL troughs: (*i*) they truncate extensive uplands that include drumlins cut into till; (*ii*) they are eroded into bedrock and, in places, the trough floors extend > 200 m below sea level (Fig. 7*b*); (*iii*) their floors slope to the north, whereas the eroding flow was upslope to the south; and (*iv*) they are steep-walled troughs with sinuous thalwegs and contain a series of enclosed depressions (Mullins et al. 1996). This combination of morphological attributes suggests that the troughs were cut by pressurized subglacial meltwater (Shaw 1996) and that the giant Finger Lakes troughs are genetically similar to the Ontario tunnel channels.

The FL bedrock channels are partially infilled with up to 270 m of sediment. As with the ORM channel fill sediment, the FL trough deposits fine upwards. Seismic profiles of these sediments show seismic facies with chaotic, high-amplitude reflections with highly irregular and hummocky tops. Some arched reflections, which are 25 m high and 0.5 km wide, correlate with coarse, rounded gravels recovered from core and even coarser gravel that halted drilling (Mullins et al. 1996). Hummocky architecture, common to the FL and ORM sequences, indicates the presence of ridges or positive bedforms (e.g., Fig. 5*c*). Such ridges in coarse gravel may be

Table 1. Similarities in terrain architecture between ORM and Finger Lakes areas

1	Large (kilometre-wide), deep (>100 m) channels form an anastomosing network; these may have functioned during different events.
2	Channels display steep-walled, undulating, longitudinal profiles that truncate adjacent strata.
3	A regional erosion surface (unconformity) is contiguous between channel bases and drumlinized uplands.
4	Coarse, gravely glaciofluvial sediments and (or) lags rest directly on the erosional surface.
5	Thick transitional sequences grade from coarse (glaciofluvial) to fine-grained, rhythmically laminated (glaciolacustrine) sediments.
6	Coarse–fine, glaciofluvial–glaciolacustrine sediments occur in overlying conformable moraine sediment sequences. Local deformation may occur due to rapid sedimentation.

buried eskers (Wellner et al. 1996), gravel bed forms (Shaw and Gorrell 1991; Pugin et al. 1999; Russell et al. 2003*a*), or in-phase wave bed forms (Brennand and Shaw 1994). Wedges of these coarse-grained sediments extend southward to the Valley Heads Moraines at the southern ends of the troughs.

Both ORM and FL channel sediments show consistent upward and down flow change in acoustic facies. Chaotic lower reflectors in the northern FL profiles interfinger down flow with closely spaced, continuous reflectors to the south (Mullins et al. 1996). The lower reflectors are inferred to indicate coarse sediment deposited by jökulhlaups from beneath the Laurentide Ice Sheet (Mullins et al. 1996). Petruccione et al. (1996) argued that the Montezuma tunnel channels in the FL system also originated by catastrophic drainage. They considered the timing of drumlin formation to have been contemporaneous with channel formation, though they did not suggest that the drumlins might also be formed by meltwater erosion. Nevertheless, their conclusion is that the drumlin and channel surfaces are integral to a common surface, the regional unconformity.

Thus, erosional uplands and deep troughs are part of a continuous erosional surface in the FL area. A single fining-upwards sedimentary sequence, indicating waning flow overlies this erosional surface. Thus, in a broad overview identical sequences are seen in the FL area and in the ORM area. As well, the channels in both systems crosscut adjacent drumlinized uplands with boulder lags strewn over upland surfaces (e.g., Fig. 6).

Summary of landform–sediment data

Almost identical landform–sediment associations are shown for two extensive areas, one to the north of Lake Ontario and one to the south around the Finger Lakes (Fig. 7; Table 1). Differences of scale between channels in the two areas are probably a result of differences in the relief through which the channels were cut. An unconformity or erosional surface is confidently traced across both areas. Two main morphological elements make up this unconformity: (*i*) erosional uplands; and (*ii*) troughs or channels. The erosional uplands are drumlinized or covered with erosional marks cut in bedrock. The troughs or channels show uphill reaches and are infilled with fining-upwards sedimentary sequences. Although the troughs and channels are eroded into the upland surfaces, it is probable that at some stage drumlin and channel formation were simultaneous (Brennand and Shaw 1994).

The evidence supports a tunnel channel interpretation for the troughs and channels in the FL area (Mullins et al. 1996; Petruccionne et al. 1996). However, Mullins et al. (1996) and Petruccionne et al. (1996) interpreted the drumlinized, upland erosional surface in terms of ice-sheet surging and direct glacial action on a deforming bed. Thus, there are differences between those that interpret the drumlins to the north in terms of meltwater erosion and those that interpret the FL drumlins in terms of bed deformation processes. Clearly, elucidating drumlin genesis is critical to understanding the regional unconformities.

Discussion

Origin of the Late Wisconsinan unconformity

A single major Late Wisconsinan unconformity is assumed here to extend north and south of Lake Ontario. This assumption is made despite the fact that the continuity of this unconformity cannot be directly mapped. A slightly younger erosional trend cuts across the postulated surface along the axis of Lake Ontario (Shaw and Gilbert 1990), a point that has been recently confirmed (Lewis et al. 2003). Nor can the northern and southern parts of the erosional surface be precisely correlated in time. It is highly unlikely given present dating techniques that the ages of these subglacial erosional surfaces can be directly established other than to say that they are both Late Wisconsinan and probably ~14 ka BP. Consequently, we are obliged to test the critical assumption that both erosion surfaces formed contemporaneously by means of a thorough discussion of field evidence tied directly to process reconstruction.

The evidence and interpretation of a Late Wisconsinan unconformity relies on high-resolution seismic surveys, detailed sediment–landform mapping and analysis, and data from boreholes, including continuous sediment core and geophysical logs. Drumlinized uplands, sculpted bedrock and a channel network on both sides of Lake Ontario mark an erosional unconformity created by an approximately north to south flow (Fig. 1). The FL troughs, which form part of the unconformity, are kilometres wide, > 150 m deep, some with undulating trough floors extending below sea level (Figs. 3*b*, 7*a*). Other channels in south-central and southeastern Ontario and in the FL area are wide, deep and sinuous, with uphill reaches. These troughs and channels were evidently formed by pressurized subglacial meltwater (e.g., Sharpe and Shaw 1989; Mullins and Hinchey 1989; Gilbert 1990; Brennand and Shaw 1994; Barnett et al. 1998; Petruccionne et al. 1996). Mullins et al. (1989), in a paper on the history of research on the origin of the Finger Lakes, pointed out that the lakes were originally explained as products of glacial erosion. The new meltwater interpretation testifies to a better understanding of glacier hydrology and more detailed study of the troughs–channels themselves and their sedimentary fills using new landform-sediment data (e.g., Russell et al. 2003*a*).

Drumlin-forming processes

There is no such agreement on the origin of the drumlins that form an essential part of the surface of unconformity (Fig. 4; Pugin et al. 1999; Petrucionne et al. 1996). It is agreed, however, that the drumlins are erosional. It is also clear that the drumlin landscape and large tracts of eroded bedrock with s-forms hold equivalent places as integral parts of the unconformity (Sharpe and Shaw 1989; Kor et al. 1991; Kor and Cowell 1998; Shaw 1996). The surface areas of drumlin fields and these eroded bedrock tracts are similar in scale, and it is very likely that they are of similar genesis. Boyce and Eyles (1991, their Fig. 2) argued that ice streams eroded drumlins in the ORM area as they deformed preexisting sediment, including sediments of the ORM. However, the drumlin surface, i.e., the surface of erosion, is commonly buried beneath the ORM sediments (Figs. 3*b*, 4*b*). Thus, there can be no doubt that drumlin formation preceded deposition of the ORM (Fig. 6). Boyce and Eyles (1991, 2000) also argued that a combination of erosion and deposition during subglacial deformation created thin till (Newmarket Till; Fig. 3*a*) in drumlins and thick till in intervening swales. Seismic profiles extending over many kilometres show a very different geometry: thick till in the drumlins and thin till in the swales (Figs. 4*a*, 4*b*; Pugin et al. 1999), related to a planar contact at the base of the till (Fig. 6). Furthermore, reflectors showing continuity between channel bases and drumlin tops crosscut till in drumlins (Figs. 4*b*–4*d*). Thus the subglacial deformation explanation for the drumlins is directly contradicted by field observation and should be rejected or be subject to major revision. Others have used the subglacial deformation hypothesis to infer drumlin origin without a critical investigation of the landform, sediment, and process links (Mullins et al. 1996; Petruccionne et al. 1996).

The meltwater hypothesis for drumlins offers a different explanation. A central point to this hypothesis is that the drumlin tracts are an extension of, and equivalent to, tracts of eroded bedrock in the erosional landscape (e.g., Shaw 1996). The simplest and most plausible conclusion is that a single agent eroded drumlins and scoured bedrock tracts contemporaneously over these regional landscapes. Kor et al. (1991), for instance, demonstrated that erosional marks in bedrock, including groups of rock drumlins with coarse boulder lags around the shores of Georgian Bay (Fig. 1), were part of an extensive and continuous field that is readily explained by broad (>100 km-wide), subglacial meltwater flows. Furthermore, the evidence for these flows requires that their instantaneous discharge was about 10^7 m^3/s. (Kor et al. 1991). Thus, a regional unconformity consists of an assemblage of channels, tracts of eroded bedrock, and drumlin fields. Since the channels and eroded bedrock are both explained by catastrophic subglacial meltwater discharges, it is fair to assume that drumlins were similarly formed (Shaw and Sharpe 1987; Shaw 1996).

Meltwater erosion explains both drumlin form and composition in ways that the subglacial deformation hypothesis cannot. The meltwater hypothesis is supported by the landscape context of the drumlins, their form, and their composition, be it sediment or bedrock (Shaw 1996). For example, hairpin furrows wrapped around the upstream ends of drumlins are well explained by horseshoe vortices in a turbulent fluid, but not by ice (e.g., Shaw and Sharpe 1987, Shaw 1994). As well, the subglacial deformation hypothesis cannot explain the many drumlins cut in hard, crystalline bedrock with superimposed, polished s-forms (Kor et al. 1991). Furthermore, lags of boulders (some with percussion marks) on these scoured rocks and on many drumlin surfaces are easily explained in terms of meltwater flow competence; conversely, such lags are difficult to explain by the deformation hypothesis. Waning flow following vortex erosion of the drumlin surface can also explain coarse gravel to sand and silt deposition on this surface. Till deformation processes, on the other hand, are clearly incompatible with this event sequence. Because the areal extent of the meltwater scoured bedrock tracts is about the same as the extent of drumlin fields, the meltwater hypothesis for drumlin formation cannot be dismissed on the basis of scale or process. The following conclusion is appropriate: where meltwater erodes hard bedrock, it produces s-forms; where it erodes sediment and poorly lithified bedrock, it produces drumlins and associated features (Fig. 2; Shaw 1996, Fig. 1). Not surprisingly there is some overlap with respect to form (Kor et al. 1991).

Inter-regional correlation

Field evidence suggests that the regional-scale unconformity with north–south orientation resulted from broad, high-magnitude and powerful subglacial meltwater flows on each side of the lake (Murray 1987; Shaw and Sharpe 1987; Sharpe and Shaw 1989; Mullins and Hinchey 1989; Shaw and Gilbert 1990; Kor et al. 1991; Gilbert 1994; Gilbert and Shaw 1994: Brennand and Shaw 1994; Lewis et al. 1996; Petruccionne 1996; Shaw 1996; Pair 1997; Kor and Cowell 1998; Lewis et al. 2003; Blasco 2001). If the unconformity to the south formed first, there would have had to be a reservoir for the subglacial meltwater that eroded the land to the south of the lake but not to the north. Similarly, if a northern unconformity formed independently of a southern one, it becomes difficult to explain where the water went without eroding the land to the to south of the lake. These difficulties are resolved if we assume that the unconformities north and south of the lake are each part of a single, regional-scale unconformity, thought to have resulted from erosion during the Algonquin Event outburst flood (Shaw and Gilbert 1990).

Other regional unconformities related to meltwater erosion

Channeled Scablands

The regional unconformity in the vicinity of Lake Ontario is carefully documented by a large number of studies (Fig. 1); however, it should not be considered exceptional. The erosional landscape of the Channeled Scablands of Washington State represents a remarkably similar set of features and processes to those described here (Bretz et al. 1969). The scabland coulees with bars covered by giant ripples are equivalent to channels with large-scale cross-beds in the ORM and FL areas. Extensive regions of scoured basalt bedrock with fluting and kettle and butte forms are equivalent to the scoured bedrock with s-form elements of the ORM and FL unconformity. The ORM and FL drumlin fields are also equivalent to the streamlined loess hills of the scablands. The scablands were eroded by subaerial flows, whereas subglacial floods explain the ORM–FL landscape erosion. Evidently, the occurrence of extremely high magnitude floods is sufficient to produce the erosional landform assemblage of regional unconformities.

Alberta

Another regional-scale unconformity relates to the Livingstone Lake outburst event (Shaw et al. 1989, 1996; Rains et al. 1993; Shaw 1996). Rains et al. (1993) mapped erosional tracts running the length of the Province of Alberta. Sjogren and Rains (1995) use digital elevation model (DEM) hillshade maps to illustrate complex scabland erosion within the flow tracts. Shaw et al. (1996) presented a DEM hillshade map for the whole of the Province of Alberta, on which the flood tracts mapped earlier by Rains et al. (1993) are prominent and confidently interpreted as glaciofluvial. Munro and Shaw (1997) and Munro-Stasiuk and Sjogren (2002) presented clear evidence that much of the hummocky terrain on the Prairies is erosional in origin and best explained as glaciofluvial. Shaw et al. (2000) showed that large-scale fluting in the flood tracts was most likely eroded by meltwater. Also, Beaney and Shaw (2000) and Beaney and Hicks (2001) showed that a complex of "giant ripples" cut into bedrock and associated tunnel channels relate to subglacial outburst floods. Thus, an impressive array of evidence supports the hypothesis that subglacial floods of the Livingstone Lake event resulted in a regionally extensive erosional surface on the Prairies.

These examples are well documented and have been central to the debate on the meltwater flood hypothesis. However, they may represent only a small proportion of the potential meltwater flows beneath the paleo-ice sheets. Unless drumlins and genetically similar subglacial bed forms have a variety of origins, it is probable that they also represent unconformities. If this is the case, floods may have burst out beneath considerable portions of the mid-latitude ice sheets.

Antarctic

Recent work shows the likelihood of similar meltwater activity beneath the Antarctic ice sheets (e.g., Sawagaki and Hirakawa 1997). These authors mapped spectacular, large-scale meltwater erosional s-forms along the Siwa Coast marginal to the East Antarctic Ice Sheet. They showed that paleocurrents derived from the s-forms relate to both paleo-ice slope and ground slope control of meltwater flow. The paleoflows show regional coherence and postulated subglacial reservoirs can be linked to the hydraulic conditions necessary to sustain this stored meltwater. Further, subglacial reservoirs are observed beneath the Antarctic ice sheets (Siegert 2000).

Observations from seismic surveys on the Antarctic Shelf further support the conclusions of Sawagaki and Hirakawa (1997) and extend the range of the expected regional unconformity into the offshore. Fluting and drumlins in sediment and bedrock in the vicinity of tunnel channels also carry s-forms with morphological similarity to hairpin scours. These forms are likely generated by horseshoe vortices within meltwater flows and are associated with furrows or lineations in the distal parts of the hairpin scours (Shaw 1994). Thus, crescentic scours and downflow lineations both record the passage of large discharges of meltwater. Ó Cofaigh et al. (2002) and Wellner et al. (2002) acknowledge that these crescentic scours indicate meltwater erosion, and Gilbert et al. (in press) and Lowe and Anderson (2002) infer catastrophic meltwater events. Others consider large-scale lineations to be products of glacial action and subglacial deformation (Shipp et al. 1999; Anderson et al. 2001; Lowe and Anderson 2002*)*. Similar scale lineations are produced by wind and inferred to be related to turbulent flow (Shaw 1996; Shaw et al. 2000). These fluvial- and eolian-derived lineations are interpreted as erosional and are related to glaciofluvial forms. Thus s-forms and lineations, now interpreted as products of subglacial deformation, are better inferred to be meltwater erosional forms. This interpretation overcomes the need to incorporate high volumes of meltwater into till (Wellner et al. 2002) and the need to produce sufficient water to erode these bed forms by steady-state melting (Ó Cofaigh et al. 2002).

Significance of regional glaciofluvial processes

Coarse deposits on the regional unconformity allow additional process inferences to be made for both the ORM and the FL areas. Coarse lags on up-flow channel floors (Barnett and Mate 1998; Petruccione et al. 1996) and large, gravel bed forms (Shaw and Gorrell 1991; Gilbert 1994; Pugin et al. 1999) within channels attest to the minimum high velocity of the subglacial flows of ~5–10 m/s. Coarse, gravelly sediments (inferred from hummocky and clinoform, high-amplitude reflectors) observed overlying the erosional surface (Fig. 5) support the interpretation of rapid, closely timed, high-energy erosion and glaciofluvial sedimentation (Shoemaker 1992; Russell et al. 2003*a*). The transition upwards from high-amplitude to lower amplitude seismic reflectors indicates a progression from high-energy to lower energy sedimentation. Similar evidence of waning flow conditions is characteristic of Icelandic surface jökulhlaup sequences (Maizels 1997). Late, rapid-flow meltwater sediments formed eskers and subaqueous fans within channels (e.g., Brennand and Shaw 1994; Russell et al. 2000) and the overlying ORM (Barnett et al. 1998; Russell et al. 1998) and FL moraines (Mullins et al. 1996).

Glaciofluvial processes were probably very significant in late-glacial times, when glacier meltwater storage was increasing as climates warmed (Shoemaker 1992). Nevertheless, recent work has focused on equating rapid ice stream events with regional deforming subglacial sediment layers (till and drumlins), and with Heinrich events (i.e., iceberg discharges), considered to be their offshore equivalents (e.g., Clark et al. 1999). In the ORM-FL data presented here, regional till sheets record sediment accumulation prior to drumlin-forming events because thick till is truncated by the regional unconformity. Therefore, the proposed meltwater flood marked by this unconformity, not drumlin sedimentation, represents the rapid-flow event. Stored subglacial meltwater may have induced and sustained surging, until subglacial water sheets became channelized (Shoemaker 1999).

The sedimentology of offshore sequences is also being increasingly linked with outburst floods (Brown and Kennett 1998; Brunner et al. 1999; Jaeger and Nittrouer 1999; Shaw et al. 1999; Zuffa et al. 2000). Therefore, analysis and improved modeling of late-glacial events require the incorporation of additional knowledge of subglacial processes (e.g., Marshall et al. 2000) and should include both outburst floods and rapid ice flow to explain event correlations from terrestrial landscapes to ocean basins and Heinrich events. For example, Rashid et al. (2000) conclude that catastrophic release of meltwater, not iceberg melt, explains the short duration of excursions towards dominance of light isotopes coinciding with Heinrich events.

Summary

The regional erosional and sedimentary architecture of the Oak Ridges Moraine area of southern Ontario is linked with the sediments and a principal erosional surface in the Finger Lakes area, New York. A regional unconformity is correlated between the two areas on the basis of formation in the Late Wisconsinan, landscape analysis and physical process arguments demonstrating that they must be contemporaneous. Stratigraphic architecture, landform associations, relative ages, boulder lags, fining-upwards channel sediments, and the regional unconformities are similar and show similar relationships in both areas. Seismic profiles, detailed mapping, and sedimentological data from continuous drillcore are the critical data that tie these architectural elements to the regional event sequence.

Outburst floods beneath the Laurentide Ice Sheet probably produced the terrain features and the basal sequences of the channel fills. The postulated sequence of events is (*i*) regional deposition of a thick Late Wisconsinan till, which may have restricted meltwater drainage at the ice bed and encouraged subglacial water storage; (*ii*) ice streaming or surging resulting from reduced basal resistance to flow in areas of meltwater storage (Shoemaker 1999); (*iii*) extensive subglacial erosion by broad flows, eroding s-forms in bedrock, drumlins, and shallow channels; (*iv*) subglacial erosion by deep channelized flow; and (*v*) rapid deposition of gravel in channels, followed by (*vi*) deposition of sand and silt under lower flow power.

The preceding list carries enormous implications for the earth system during deglaciation. Regional-scale meltwater discharge events and ice-sheet surging explain many of the tantalizing aspects of the sedimentology and isotopic chemistry of the North Atlantic at this time (Bond et al. 1992). In particular, a braid plain on the floor of the Labrador Sea contains an enormous volume of sand and gravel (700 km long, 120 km wide, and 100–200 m thick) and the currents that deposited these sediments destroyed levees more that 200 m high (Hesse et al. 2001). These are not normal deposits on abyssal plains. They demand extreme sedimentation events, and outburst floods must be considered as a potential cause of such events. Ventilation of the oceans by very large volumes of cold, turbid, fresh water would have also had major effects on ocean stratification and sea-surface temperature as deposition of sediment reduced density and caused cold underflows to rise as plumes through the water column. Mixing of the isotopically light meltwater with ocean water would also have changed the isotopic composition of the North Atlantic. Life in the water column and on the seabed would have changed as a result of the marked changes in environmental conditions. Sea-ice extent and its seasonal distribution would have changed together with the climate for at least the northern hemisphere (Shaw 1996). To date, there has been no attempt to investigate these presumed effects of extreme discharges on late-glacial ocean and climate evolution, prior to the formation of large proglacial lakes.

With the exception of the Channeled Scablands (Shaw et al. 1999), the central role of meltwater erosion in regional-scale landscape formation is not well received (e.g., Shaw et al. 1998). For the scabland erosional unconformity, there is a clear sedimentary record of depositional events in the Pacific Ocean (Brunner et al. 1999; Zuffa et al. 2000), but there is no unequivocal correlation of catastrophic flood events and sedimentary sequences in the North Atlantic (e.g., Hesse and Khodabakhsh 1998; Rashid et al. 2000). The difficulty seems to lie in the number of alternative mechanisms (especially ice rafting) that might have generated the sedimentary sequences of, for example, the Labrador Sea abyssal plain. The task of relating sedimentary units and the depositional events that were responsible for them is in its infancy. Nonetheless, just as the marine isotopic record revolutionized terrestrial paleoclimate studies, we anticipate greater clarity in the interpretation of terrestrial deglaciation (e.g., erosional events) with improved understanding of marine sedimentation. At the same time, studies such as this one present compelling evidence for large-scale and rare erosive floods. As a result, researchers working, for example, on continuous cores of Late Wisconsinan sediment in the North Atlantic off the eastern seaboard of the United States should be alert to the likelihood of sedimentary sequences related to catastrophic flood deposits from the Algonquin event appearing in the cores.

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References

Anderson, J.B., Wellner, J.S., Lowe, A.L., Mousla, A.B., and Shipp, S.S. 2001. Footprint of the expanded West Antarctic Ice Sheet: ice stream history and behavior. Geological Society of America Today, **11**(10): 4–9.

Barnett, P.J. 1990. Tunnel valleys: evidence of catastrophic release of subglacial meltwater, central-southern Ontario, Canada. *In* Abstracts with Programs. Northeastern Section Geological Society of America, Syracuse, N.Y., p. 3.

Barnett, P.J. 1992. Quaternary geology of Ontario. *In* Geology of Ontario. *Edited by* P.C. Thurston, H.R., Williams, R.H., Sutcliffe, and G.M. Stott. Ontario Geological Survey, Special Vol. 4, Part 2, Toronto, Ont., pp. 1011–1088.

Barnett, P.J., and Mate, D.J. 1998. Quaternary geology, Beaverton area; Ontario Geological Survey, Map 2560, scale 1 : 50 000.

Barnett, P.J., Cowan, W.R., and Henry, A.P. 1991. Quaternary geology of Ontario, southern sheet. Ontario Geological Survey, Map 2556, scale 1 : 1 000 000.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F., and Pugin., A. 1998. On the origin of the Oak Ridges Moraine. Canadian Journal of Earth Sciences, **35**: 1152–1167.

Beaney, C.L., and Hicks, F.E. 2000. Hydraulic modelling of subglacial tunnel channels, South-east Alberta, Canada. Hydrological Processes. **14**: 2545–2557.

Beaney, C.L., and Shaw, J. 2000. The subglacial geomorphology of southeast Albert: evidence for subglacial meltwater erosion. Canadian Journal of Earth Sciences, **37**: 51–61.

Bernard, C. 1971. Les marques sous-glaciares d'aspect plastique sur la roche en place (p-forms): Observations sur la bordure bouchier canadien et examen de la question. Révue de Géographie Montréal, **25**(2): 111–127.

Blasco, S. 2001. Geological history of Fathom Five National Marine Park over the past 15, 000 years. *In* Ecology, culture and conservation of a protected area: Fathom Five National Park, Canada. *Edited by* S. Parker and M. Munawar, Ecovision. World Monograph Series, Backhuys Publishers, Leiden, The Netherlands, pp. 45–62.

Bond, G., Heinrich, H., Broecker, W., Labeyree., I., McManus, J., Andrews, J., Huin, S., Jantschik, R., Clason, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S. 1992. Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. Nature, **360**: 245–249.

Boyce, J.I., and Eyles, N. 1991. Drumlins carved by deforming till streams below the Laurentide Ice Sheet. Geology, **19**: 787–790.

Boyce, J.I., and Eyles, N. 2000. Architectural analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. Geological Society of America Bulletin, **112**: 98–118.

Boyce, J.I., Eyles, N., and Pugin, A. 1995. Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario. Canadian Journal of Earth Sciences, **32**: 1331–1349.

Brennand, T., and Shaw, J. 1994. Tunnel channels and associated landforms: their implication for ice sheet hydrology. Canadian Journal of Earth Sciences, **31**: 502–522.

Brennand, T.A., Logan, C., Kenny, F., Moore, A., Russell, H.A.J., Sharpe, D.R., and Barnett, P.J. 1998. Bedrock Topography of the Greater Toronto and Oak Ridges Moraine NATMAP areas, southern Ontario. Geological Survey of Canada, Open File 3419, map scale 1 : 200 000.

Bretz, J.H. 1969. The Lake Missoula floods and the Channeled Scabland. Journal of Geology. **77**: 505–543.

Brown, P.A., and Kennett, J.P. 1998. Mega flood erosion and meltwater plumbing changes during the last North American deglaciation recorded in the Gulf of Mexico sediments. Geology, **26**: 599–602.

Brunner, C.A., Normark, W.R., Zuffa G.G., and Serra, F. 1999. Deep-sea sedimentary record of the Late Wisconsin cataclysmic floods from the Columbia River. Geology, **27**(5): 463–466.

Cai, J., Powell, R.D., Cowan E.A., and Carlson, P.R. 1997. Lithofacies and seismic-reflection interpretation of temperate glacimarine sedimentation in Tarr Inlet, Glacier Bay, Alaska. Marine Geology, **143**: 5–37.

Clark, P.U., Alley, R.B., and Pollard, D. 1999. Northern hemisphere ice-sheet influences on global climate change. Science, **286**: 1104–1111.

Davies, T.A., and Austin, J.A., Jr. 1997. High-resolution 3D seismic reflection and coring techniques applied to late Quaternary deposits on the New Jersey shelf. Marine Geology, **143**: 137–149.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F., and Eyles, C.H. 1985. The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario basin, Canada. Geoscience Canada, **12**: 22–32.

Eyles, N., Mullins, H.T., and Hine, A.C. 1991. The seismic stratigraphy of Okanagan Lake, British Columbia: a record of rapid deglaciation in a deep fiord-lake basin. Sedimentary Geology, **73**: 13–41.

Fisher, T.G., and Taylor, L.D. 2002. Sedimentary and stratigraphic evidence for subglacial flooding, south-central Michigan, USA. Quaternary International, **90**: 87–115.

Fligg, K., and Rodrigues, B. 1983. Geophysical well log correlations between Barrie and the Oak Ridges Moraine. Water Resources Branch, Ontario Ministry of the Environment, Map 2273.

Gareau, P.L., and Lewis, C.F.M., In press. Digital reconstruction of the areas, volumes, and geography of the paleo-Great Lakes (11.3–7.7 ka), Geological Survey of Canada, Open File Report.

Gilbert, R. 1990. Evidence for the subglacial meltwater origin and late Quaternary lacustrine environment of Bateau Channel, eastern Lake Ontario. Canadian Journal of Earth Sciences, **27**: 939–945.

Gilbert, R. 1994. A field guide to the glacial and postglacial landscape of southeastern Ontario and part of Quebec. Geological Survey of Canada, Bulletin 453.

Gilbert, R. 2000. The Devil Lake pothole (Ontario): evidence of subglacial fluvial processes. Géographie physique et Quaternaire, **54**(2): 245–250.

Gilbert, R., and Shaw, J. 1994. Inferred subglacial meltwater origin of lakes on the southern border of the Canadian Shield. Canadian Journal of Earth Sciences, **31**: 1630–1637.

Gilbert, R., Domack, E.W., and Camerlenghi, A. In press. Glacial history of the Greenpeace Trough: ice sheet to ice shelf transition in the northwestern Weddell Sea. *In* Antarctic Peninsula Climate Variability: A Historical and Paleoenvironmental Perspective. *Edited by* E. Domack et al., American Geophysical Union, Special Publication, 2003.

Gorrell, G., and Brennand, T.A. 1997. Surficial Geology of the Rice Lake (31 D/1) 1 : 50 000 NTS map sheet, southern Ontario. Geological Survey of Canada Open File 3332, map scale 1: 50 000.

Gwyn, Q.H.J., and DiLabio, R.N.W. 1973. Quaternary geology of the Newmarket area, southern Ontario. Ontario Division of Mines, Preliminary map P. 836, scale 1 : 50 000.

Hesse, R., and Khodabakhsh, S. 1998. Depositional facies of late Pleistocene Heinrich events in the Labrador Sea. Geology, **26**(2): 103–106.

Hesse, R., Klaucke, I., Khodabakhsh, S., Piper, D.J.W., Ryan, W.B.F., and NAMOC study group. 2001. Sandy submarine braid plains: potential deep-water reservoirs. American Association of Petroleum Geologists, **85**(8): 1499–1521.

Jaeger, J.M., and Nittrouer, C.A. 1999. Marine record of surge-induced outburst floods from the Bering Glacier, Alaska. Geology, **27**(9): 847–850.

Karrow, P.F. 1967. Pleistocene geology of the Scarborough area. Ontario Department of Mines Geological Report no. 46, Toronto, Ont.

Karrow, P.F., and Occhietti, S. 1989. Quaternary geology of the St. Lawrence lowlands of Canada. *In* Quaternary geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada, Geology of Canada, no. 1 (also Geological Society of America, The geology of North America, Vol. K-1), pp. 321–389.

Kor, P.S.G., and Cowell, D.W. 1998. Evidence for catastrophic subglacial meltwater sheetflood events on the Bruce Peninsula. Canadian Journal of Earth Sciences, **35**: 1180–1202.

Kor, P., Shaw, J., and Sharpe, D.R. 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario, a regional review. Canadian Journal of Earth Sciences, **28**(4): 623–642.

Lewis, C.F.M., and Sly, P.G. 1971. Seismic profiling and geology of the Toronto waterfront area of Lake Ontario. *In* Proceedings of the 14th Great Lakes Research Conference. International Association of Great Lake Research, pp. 303–354.

Lewis, C.F.M., Blasco, S.M., Cameron, G.D.M., King, E.L., Mayer, L.A., Shaw, J., and Todd, B.J. 1996. Were the Ontario and Erie basins swept by catastrophic meltwater flooding? Geological Society of America Northeastern Section Meeting, Buffalo, N.Y., March 21–23, 1996. GSA Abstracts with Programs, p. 76.

Lewis, C.F.M., Mayer, L.A., Cameron, G.D.M., and Todd, B.J. 1997. Drumlins in Lake Ontario. *In* Glaciated continental margins: an atlas of acoustic images. *Edited by* T.A. Davies, T. Bell, A.K. Cooper, H. Josenhans, L. Ployak, A. Solheim, M.S. Stoker, and J.A. Stravers, Chapman and Hall, London, U.K., pp. 48–50.

Lewis, C.F.M., Barnett, P.J., Blasco, S.M., and Cameron, G.D.M. 1999. Subglacial erosion of diamicton beneath the Erie Lobe of the Laurentide Ice Sheet about 13.5 Ka. *In* CANQUA–CGRC 1999, University of Calgary, Calgary, Alta., August 23–27, 1999. Canadian Quaternary Association and Canadian Geomorphology Research Group, Program and Abstracts, p. 41.

Lewis, C.F.M., Blasco, S.M., Forsyth, D.A., Mayer, L.A., Dijkstra, S.J., Jacobi, R.D., Todd, B.J., Parrott, D.R., and Coakley, J.P. 2003. Do Quaternary sediments register paleoseismicity or neotectonic rejuvenation of ancient faults beneath Lake Ontario? *In* Geological Society of America Northeastern Section and Atlantic Geoscience Society, Halifax, N.S., March 27–29, 2003. Abstract with Program, Vol. 35, No. 3 p. 77.

Logan, C., Russell, H.A.J., and Sharpe, D.R. 2001. Regional three-dimensional stratigraphic modelling of the Oak Ridges Moraine area, southern Ontario. *In* Current research 2001-D1, Geological Survey of Canada, Ottawa, Ontario, 19 p.

Lowe, A.L., and Anderson, J.B. 2002. Reconstruction of the West Antarctic ice sheet in Pine Island Bay during the Last Glacial Maximum and its subsequent retreat history. Quaternary Science Reviews, **21**: 1879–1897.

Lysa, L., and Vorren, T.O. 1997. Seismic facies and architecture of ice-contact submarine fans in high-relief fjords, Troms, Northern Norway. Boreas, **26**: 309–328.

Maizels, J. 1997. Jökulhlaup deposits in proglacial areas. Quaternary Earth Science Reviews, **16**: 793–819.

Marshall, S.J., Tarasov, L., Clarke, G.K.C., and Peltier, W.R. 2000. Glaciological reconstruction of the Laurentide Ice Sheet: physical processes and modelling challenges. Canadian Journal of Earth Sciences, **37**(5): 769–793.

Martini, I.P., and Brookfield, M.E. 1995. Sequence analysis of upper Pleistocene (Wisconsinan) glaciolacustrine deposits of the north-shore bluffs of Lake Ontario, Canada. Journal of Sedimentary Research, **B65**(3): 388–400.

Muller, E.H., and Caldwell, D.H. 1986. Surficial Geologic map of New York-Fingers Lakes sheet. Albany New York State Museum, Geological Survey Map and Chart Series No 40, scale 1 : 250 000.

Mullins, H.T., and Hinchey, E.J. 1989. Erosion and infill of New York Finger Lakes: Implications for Laurentide Ice Sheet deglaciation. Geology, **17**: 622–625.

Mullins, H.T., Hinchey. E.J., and Muller, E.H. 1989. Origin of New York Finger Lakes: a historical perspective. Northeastern Geology, **11**: 166–181.

Mullins, H.T., Hinchey, E.J., Wellner, R. W., Stephens, D.B., Anderson, W.T., Dwyer, T.R., and Hine, A.C. 1996. Seismic stratigraphy of the Finger Lakes: a continental record of Heinrich event H-1and Laurentide Ice Sheet instability. *In* Subsurface geologic investigations of New York Finger Lakes: implications for late Quaternary deglaciation and environmental change. *Edited by* H.T. Mullins and N. Eyles. Geological Society of America, Special Publication 311, pp. 1–35.

Munro, M., and Shaw, J. 1997. Erosional origin for hummocky terrain, south central Alberta, Canada. Geology, **25**: 11027–1030.

Munro-Stasiuk, M., and Sjogren, D.B. 2002. Evidence for province-wide water storage and catastrophic drainage beneath the Laurentide Ice Sheet, Alberta, Canada. *In* The extremes of the extreme: extraordinary floods. Proceedings of a symposium held at Reykjavik, Iceland, July 2000. IAHS (Internationl Association of Hydrological Sciences) publication no. 271, pp. 113–119.

Novak, B., and Stoker, M.S. 2001. Late Weishelian glacimarine depositional processes in the southern Skagerrak revealed by high-resolution seismic facies analysis. Marine Geology, **178**: 115–133.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J., and Morris, P. 2002. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. Geophysical Research Letters, **29**: 41-1 – 41-4.

Pair, D.L. 1997. Thin film, channelized drainage, or sheetfloods beneath a portion of the Laurentide Ice Sheet: an examination of glacial erosion forms, northern New York State, U.S.A. Sedimentary Geology, **111**: 199–215.

Patterson, C.J., Regis, R., and Rausch, D.E. 2003. Subglacial drainageways preserved on the floors of lakes Superior and Michigan. *In* Geological Society of America Annual Meeting, Seattle, Wash., November 2003.

Petruccione, J.L., Wellner, R.W., and Sheridan, R.E. 1996. Seismic reflection investigations of Montezuma wetlands New York State: evolution of a Late Quaternary subglacial meltwater channel system. *In* Subsurface geologic investigations of New York Finger Lakes: implications for late Quaternary deglaciation and environmental change. *Edited by* H.T. Mullins and N. Eyles. Geological Society of America, Special Publication 311, pp. 77–89.

Pugin, A., Pullan S.E., and Sharpe, D.R. 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences, **36**(3): 409–432.

Pugin, A., Pullan, S.E.,. Burns, R.A,Douma, M.,and R.L. Good. 2001. High-resolution, multichannel, marine seismic surveying using a small airgun source. < http://sts.gsc.nrcan.gc.ca/orm/pdf/Simcoe.pdf >.

Rains, B., Shaw, J., Skoye, R., Sjogren, D., and Kvill, D. 1993. Late Wisconsin subglacial megaflood paths in Alberta. Geology, **21**: 323–326.

Rashid, H., Hesse, R., and Piper, D.J.W.P. 2000. Was it melt-water outflow or ice-sheet discharge? A high-resolution study of ice-sheet dynamics from the high-latitude sector of the LIS during the LGM. EOS, **81**(19): p. S21.

Russell, H.A.J. 2001. The record of high-energy episodic sedimentation in the western Oak Ridges Moraine, southern Ontario. Unpublished Ph.D. thesis, Department of Earth Sciences, University of Ottawa, Ottawa, Ont.

Russell, H.A.J., and Sharpe, D.R. 2002. The role of lithofacies and sedimentological models in mapping heterogeneity of the Oak Ridges Moraine glacifluvial complex, southern Ontario, Canada, SEPM/IAS Research Conference Ancient and Modern Coastal Plain Depositional Environments: Aquifer heterogeneity and environmental implications. Society of Economic Paleontologists and Mineralogists (SEPM), Charleston, South Carolina, March 24–27, 2002. Conference CD.

Russell, H.A.J., Sharpe, D.R., and Arnott, R.W.C. 1998. A preliminary report on the sedimentology of the Oak Ridges Moraine, Humber River watershed, southern Ontario. *In* Current research 1998-C. Geological Survey of Canada, pp. 155–166.

Russell, H.A.J., Sharpe, D.R., Pullen, S.E., and Barnett, P.J. 2000. Form and sedimentary fill of tunnel channels beneath the Oak Ridges Moraine, southern Ontario: the Holland Marsh – King City channel system. Geological Survey of Canada, Open File 3841.

Russell, H.A.J., Arnott, R.W.C., and Sharpe, D.R. 2003*a*. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada. Sedimentary Geology, **160**(1–3): 33–55.

Russell, H.A.J., Sharpe, D.R., Brennand, T.A., Barnett, P.J., and

Logan, C. 2003*b*. Tunnel channels of the Greater Toronto and Oak Ridges Moraine Areas, Southern Ontario: Geological Survey of Canada, Open File 4485, map scale 1 : 250 000.

Sawagaki, T., and Hirakawa, K. 1997. Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. Geografiska Annaler, **79A**: 223–238.

Sharpe, D.R., and Shaw, J. 1989. Erosion of bedrock by subglacial meltwater, Cantley, Québec. Bulletin of the Geological Society of America, **101**(8): 1011–1020.

Sharpe, D.R., Barnett, P.J., Brennand T.A., Finley, D., Gorrell, G., and Russell, H.A. 1997. Glacial geology of the Greater Toronto and Oak Ridges Moraine areas, southern Ontario. Geological Survey of Canada Open File 3062, map scale 1 : 200 000.

Sharpe, D.R., Hinton, M., Russell, H.A.J., and Barnett, P.J. 1998. Regional geology and hydrogeology of the Oak Ridges Moraine area, southern Ontario; Field Trip Guide 7. Geological Society of America, Annual Meeting, Toronto, Ont., Canada.

Sharpe, D.R., Dyke, L., Gorrell, G., Hinton, Good, R.L., Hunter, J.A., and Russell, H.A. 2003*a*. GSC High-quality boreholes, “Golden Spikes”, Oak Ridges Moraine, southern Ontario; Geological Survey of Canada, Open File 1670.

Sharpe, D.R., Pugin, A., Pullan S.E., and Gorrell, G. 2003*b*. Application of seismic stratigraphy and sedimentology to regional hydrogeological investigations: an example from Oak Ridges Moraine, southern Ontario, Canada. Canadian Geotechnical Journal, **40**: 1–20.

Shaw, J. 1988. Subglacial erosional marks, Wilton Creek, Ontario. Canadian Journal of Earth Sciences, **25**: 1256–1267.

Shaw, J. 1994. Hairpin erosional marks, horseshoe vortices and subglacial erosion. Sedimentary Geology, **91**: 269–284.

Shaw, J. 1996. A meltwater model for Laurentide subglacial landscapes. *In* Geomorphology sans frontières, *Edited by* S.B. McCann and D.C. Ford. Publication no. 6, International Association of Geomorphologists. John Wiley and Sons Limited, Toronto, Ont., pp. 181–236.

Shaw, J., and Gilbert, R. 1990. Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. Geology, **18**: 1169–1172.

Shaw, J., and Gorrell, G.A. 1991. Subglacially formed dunes with bimodal and graded gravel in the Trenton drumlin field, Ontario, Canada. Géographie physique et Quaternaire, **45**(1): 21–34.

Shaw, J., and Sharpe, D.R. 1987. Drumlin formation by subglacial meltwater erosion. Canadian Journal of Earth Sciences, **24**: 2316–2322.

Shaw, J., Kvill, D., and Rains, B. 1989. Drumlins and catastrophic subglacial floods. *In* Subglacial bedforms; drumlins, Rogen moraine and associated subglacial bedforms. *Edited by* J. Menzies and J. Rose. Sedimentary Geology, **62**: 177–202.

Shaw, J., Rains, B., and Weissling, L.E. 1996. Laurentide subglacial outburst floods; landform evidence from digital elevation models. Canadian Journal of Earth Sciences, **33**: 1154–1168.

Shaw, J., Munro-Stasiuk, M., Rains, R.B., Sharpe, D.R., Pugin, A., Pullan, S., Lewis, C.F.M., Todd, B.J., Gilbert, R.G., and Sjogren, D. 1998. *In* Regional landscape unconformities formed beneath the Laurentide Ice Sheet. Geological Society of America, Annual Meeting, Toronto, Ont. Abstract.

Shaw, J., Munro-Stasiuk, M., Sawyer, B., Beaney, C., Lesemann, J-E., Musacchio, A., Rains, B., and Young, R.R., 1999. The Channeled Scabland: back to Bretz? Geology, **27**(7): 605–608.

Shaw, J., Faragini, D.M., Kvill, D.R., and Rains, R.B. 2000. The Athabasca fluting field, Alberta, Canada: implications for the formation of large-scale fluting (erosional lineations). Quaternary Science Reviews, **19**: 950–980.

Shipp, S.S., Anderson, J.B., and Domack, E.W. 1999. Seismic signature of the late Pleistocene fluctuation of the West Antarctic Ice Sheet system in Ross Sea: a new perspective, Part 1. Geological Society of America Bulletin, **111**: 1486–1516.

Shoemaker, E.M. 1992. Water sheet outburst floods from the Laurentide Ice Sheet. Canadian Journal of Earth Sciences, **29**(6): 1250–1264.

Shoemaker, E.M. 1999. Subglacial water-sheet floods, drumlins and ice-sheet lobes. Journal of Glaciology, **36**(4): 323–329.

Siegert, M.J. 2000. Antarctic subglacial lakes. Earth Science Review, **50**: 29–50.

Sjogren, D., and Rains, R.B. 1995. Glaciofluvial erosional morphology and sediments of the Coronation–Spondin scabland, east-central Alberta. Canadian Journal of Earth Siences, **32**: 565–578.

Syvitski, J.P.M., Stoker, M.S., and Cooper, A.K. 1997. Seismic facies of glacial deposits from marine and lacustrine environments. Marine Geology, **143**: 1–4.

Tinkler, R.J., and Stenson, R.E. 1992. Sculpted bedrock forms along the Niagara Escarpment, Ontario. Géographie physique et Quaternaire, **46**: 195–207.

Todd, B.J., and Lewis, M.C.F. 1993. A reconnaissance geophysical survey of the Kawartha Lakes and Lake Simcoe, Ontario. Géographie physique et Quaternaire, **47**: 313–323.

Todd, B.J., Hunter, J.A.M., Good, R.L., Burns, R.A., Douma, M., Pullan, S.E., and Lewis, M.C.F. 2003. Expedition report: MV J. Mackay, 1992–1993, Lake Simcoe, Ontario. Geological Survey of Canada, Open File 3037.

Vanderburgh, S., and Roberts, M.C. 1996. Depositional systems and seismic stratigraphy of a Quaternary basin, North Okanagan Valley, British Columbia. Canadian Journal of Earth Sciences, **33**: 917–927.

Wellner, R.W., Sheridan, R.E., and Petruccione, J.L 1996. Correlation of drill-core and geophysical results from Canandaigua Lake Valley, New York: evidence for rapid lat glacial sediment infill. *In* Subsurface geologic investigations of New York Finger Lakes: implications for late Quaternary deglaciation and environmental change. *Edited by* H.T. Mullins and N. Eyles. Geological Society of America, Special Publication 311, pp. 37–50.

Wellner, J.S., Lowe, A.S., Shipp, S.S., and Anderson, J.B. 2002. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: Implications for ice behavior. Journal of Glaciology, **47**: 397–411.

Zuffa, G.G., Normark, W.R., Serra, F., and Brunner, C.A. 2000. Turbidite megabeds in an oceanic rift valley recording jökulhlaups of late Pleistocene glacial lakes of the western United States. Journal of Geology, **108**: 253–274.