In A. A. Snelling (Ed.) (2008). Proceedings of the
Sixth International Conference on Creationism (pp. 357–370).
Pittsburgh, PA: Creation Science Fellowship and
Dallas, TX: Institute for Creation Research.

Catastrophic Subglacial Drainage and Rapid Landscape Formation in Canada, with Special Emphasis on the Niagara Escarpment

Emil Silvestru, Ph.D., Creation Ministries International, 5–420 Erb St. W, Suite 213, Waterloo, Ontario N2L 6K6, Canada

Abstract

The concept of subglacial sheetfloods has gained momentum in recent years and some authors have explained certain features of the Niagara Escarpment as caused by such events. However, this author found enough evidence in the field that the entire Niagara Escarpment was created by such floods. The geographic distribution and the individual characteristics of potholes as well as similarities between subglacial flow conditions and karst drainages strongly argue for a set of events linked in a close sequence that are responsible for the catastrophic genesis of the Niagara Escarpment. Meltwater accumulation under the Laurentide Ice Sheet coupled with englacial pseudokarst has resulted in at least two episodes of subglacial sheetfloods and the rapid disintegration of the ice sheet. As large chunks of the ice sheet were ripped away from the main body and resettled as separate "islands," flow and erosional patterns consistent with present-day glacial sediments formed. For the young earth creationist geoscientist such a scenario does not only provide valid arguments for rapidly forming geomorphology in the Late Quaternary but also provides valuable insights to the mechanics of flood erosion.

Keywords

Niagara escarpment, Subglacial sheetfloods, Subglacial erosion, Catastrophic, Englacial karst, Canada.

Introduction

The Michigan Basin and the Niagara Escarpment represent major components of North American geology and geomorphology. Charles Lyell's visit in the area in 1841 and his re-writing of the geologic time frame by use of the Niagara Falls and gorge as a time marker gave Niagara Escarpment a major role in the history of modern geology. In his book *Guide to the Geology of the Niagara Escarpment*, the late Dr. Walter M. Tovell (1992, p. 3573) wrote: "Time was to Charles Lyell what gravity was to Isaac Newton, or DNA was to Watson and Crick."

Niagara Escarpment is essentially a rather strange, half-circular cuesta (a sinuous ridge with a gentle slope on one side and a cliff—escarpment—on the other), extending from northern New York State, through most of Southern Ontario, Bruce Peninsula, Manitoulin Island, back south through Michigan (on the western shores of Lake Michigan) into Wisconsin. The total length of the Niagara Escarpment is well in excess of 700 km. The escarpment proper is far from being continuous, often times the cliffs totally disappear under thick glacial deposits or are eroded away along perpendicular valleys (Figure 1). The cliffs are formed by the carbonate (dolostone) sequence of the Ordovician-Silurian sedimentary suite that constitutes the bedrock in this area. The Silurian dolostone overlies softer terrigenous sediments. The width of the cuesta proper, that is, the segment behind the cliffs in which the escarpment lithology is exposed, reaches its maximum width (a couple of kilometers) in the Bruce Peninsula. Nevertheless,

Figure 1. General map of The Niagara Escarpment and Michigan Basin. Retrieved from http://commons.wikimedia.org/wiki/Image:November_gale.png with additions.

most of the time the Niagara Escarpment stands as a well defined irregularity inside a rather dull, rolling-hill type of landscape that characterizes most of southern Ontario and northern Michigan, with its most spectacular segment along the eastern side of the Bruce Peninsula, creating the scenic cliffs that overlook the Georgian Bay.

It is difficult to select from the vast literature published on the Niagara Escarpment as this landmark is one of the most studied North American geological sites and almost mandatory field trip for many geologists. For the Canadian ones, Tovell's book is probably the ultimate reference, including some of the first research on the Niagara Escarpment like Dow (1921); Hennepin (1698); Kindle and Taylor (1913); Levrett and Taylor (1915); Lyell (1845) .

Subglacial floods on larger scale have entered the scientific literature relatively recently (probably early 1980s), but not until the work of Shaw (1983, 1988, 1989, 1994, 1996, 2002; Shaw & Kvill, 1984; Shaw & Sharpe, 1987; Shaw & Gilbert, 1990; Shaw, Faragini, Kvill, & Rains, 2000) have they been considered as major erosional agents. Shaw's research itself began mostly as an alternative explanation to subglacial bedforms, especially drumlins. As his studies extended, so did the areas that showed signs of subglacial erosion in North America until a regional, even sub-continental scale became noticeable. Gigantic amounts of meltwater have been postulated as accumulating beneath the Laurentide Ice Sheet, being periodically released through massive flooding events. Much of the areal—as opposed to channelized—erosional effects are believed to have occurred underneath the ice. Thus, mysterious large-scale meandering features in the middle of flat areas became explainable.

The Niagara Escarpment has been used as a counter argument for a young-earth, biblical time frame, ever since Lyell (1873) "calculated" a 35,000-year age of the Niagara Gorge and falls. Though catastrophic erosion by sudden drainage of proglacial Lake Agassiz is a valid scientific explanation, no sign of it is found in any of the tourist signs that so much shape the mind of visitors, and very few textbooks even mention Lake Agassiz. It seems like most of the emphasis regarding this Late Pleistocene episode is on its northerly subglacial release into Hudson Bay (Tarasov & Peltier, 2006). Few researchers have looked at features along the Niagara Escarpment that may support a southern drainage of Lake Agassiz also.

By investigating the existence of such drainage, this paper aims to provide arguments not only for the magnitude of subglacial erosion, but also a possible means for estimating global erosion and patterns during the Genesis Flood. No quantitative data is otherwise available on a large (subcontinental) scale, and these subglacial floods can therefore be seen as excellent laboratories for diluvial geomorphology. On the other hand, such a scenario tackles head-on the uniformitarian assumptions of the old-age interpretation of the Niagara Escarpment, and by extension, the whole two million year Quaternary timeframe evolutionary geology has built based on those assumptions.

Previous Studies

Ever since the emergence of glaciology, subglacial erosion has been perceived as mostly the result of the mechanical interaction between ice and the rock substrate (plucking and abrasion). This was most likely due to alpine glaciers (generally cold-based) being for a long time the only "live object of study". Moving subglacial water, although quite a visible element in some alpine settings, has been assigned little importance. Even recent major textbooks consider the bulk subglacial erosion as the result of plucking and ablation (Miller, 2002).

In 1979, Cox tried to link drumlin and other glacial features to a diluvial origin, rather than ice transport (Cox, 1979). He had also suggested that potholes on the Niagara Escarpment had a diluvial origin. Shaw and others (Shaw, 1983, 1988, 1989, 1996; Shaw & Kvill, 1984; Shaw & Sharpe, 1987) have gradually built up evidence that drumlins (Shaw, Kvill, & Rains, 1989) are the result of sediments accumulating by water transport inside negative (melt-generated) forms on the bottom of the glacier/ice sheet. Shaw also explained many of the linear and crescentic scourings of the bedrock as meltwater erosional features. It is worth mentioning that, in a most unusual gesture, Shaw has fully acknowledged Cox's priority in proposing an erosional origin of drumlins, and that he discovered Cox's model in the *Creation Research Society Quarterly* through an internet search. It is very rare to find creationist research positively referenced in secular journals (Shaw, 2002)!

Except for Shaw, all the above refer to meltwater accumulated in lakes at the edge of the melting ice sheets. Shaw has proposed subglacial meltwater floods which would basically imply under-pressure flow (similar in a way to conduit flow) discharging massive under-ice reservoirs. His idea was used to explain some strange erosional features on other continents too, like the ones in Antarctica (Denton & Sugden, 2005; Lewis, Marchant, Kowalewski, Baldwin, & Webb, 2006; Lowe & Anderson, 2003) and Europe (north-central Ireland) (Knight, 2002). The formation of the English Channel has also been recently explained as a catastrophic flood feature (Gupta, 2005; Gupta, Collier, Palmer-Felgate, & Potter, 2007; Leake, 2006).

Subglacial Meltwater Floods in Canada

The proglacial Lake Agassiz, which at its maximum extended from eastern Alberta to western Ontario, has been linked to the Younger Dryas Pleistocene episode (Broecker, 1987; Broecker et.al., 1989). It was inferred that a sudden change (probably catastrophic) in the drainage of the lake (eastward towards the St Lawrence River) triggered a disruption of thermohaline circulation system that was responsible for the drastic cooling during the Younger Dryas. Drainage northward (at a later stage) underneath the Laurentide Ice Sheet was also proposed (Hillaire-Marcel, de Vernal, Weaver, Fischer, & Solignac, 2004). As mentioned before, Shaw has already advanced the idea of sheetflow bursts of meltwater from underneath the Laurentide Ice Sheet. Two major outburst (flooding) episodes in the area were proposed: the Algonquin Event which "crossed a broad area in the eastern Great Lakes region" with a roughly north-south direction of the drainage, and later the Ontarian Event along Lake Ontario and into Lake Erie, which means a northeast to southwest direction of the drainage (Shaw & Gilbert, 1990; Shaw, Rains, Eyton, & Wielsing, 1996). Shaw, Faragini, Kvill, & Rains (2000) have also presented valid arguments for similar processes in Alberta, namely a subglacial flooding episode they dubbed the Lake Livingstone Event and which is believed to have contributed to a 0.23 m rise in sea level within weeks (Shaw, 2002). Kor and Cowell (1998) presented a more detailed postulated path for what they called the "Georgian Bay subglacial sheetfloods" (Figure 2) which in the larger context are part of Shaw's Ontarian Event, since the main direction of the drainage was northeast–southwest.

It is believed that such bursts (sheetfloods) are the results of massive storage basins underneath the ice sheet, and that consequently after discharge (flood event) the storage basins could recharge leading to recurrent flooding episodes (Munro-Stasiuk, Fisher, & Nitzsche, 2005; Shaw, 2002). The storage area for the Algonquin and Ontarian events is believed to have been around James Bay underneath the Laurentide Ice Sheet.

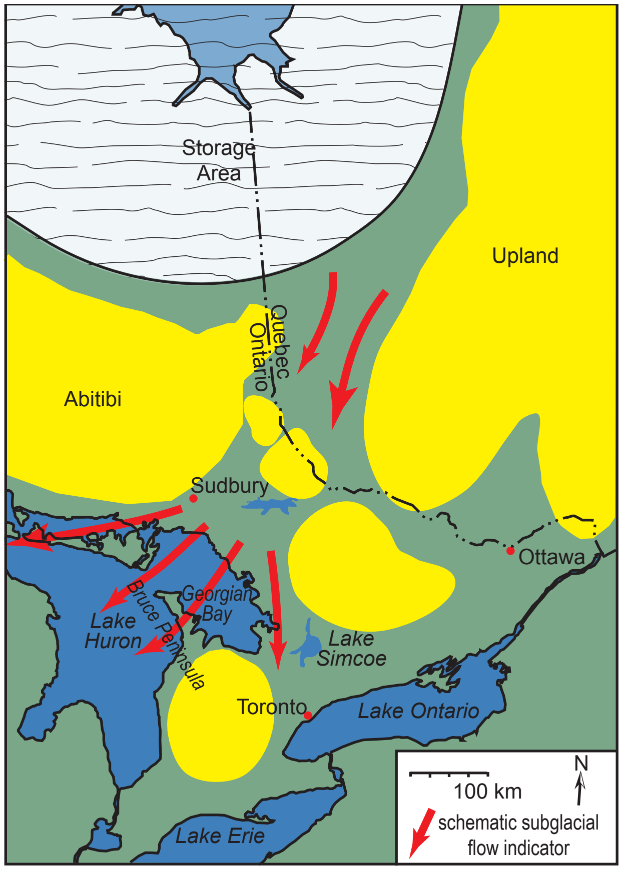

Figure 2. Postulated path of Georgian Bay subglacial sheetflood (Kor & Cowell, 1998). Such a path is confirmed by this author's field research and is consistent with the excavation of the entire Niagara Escarpment and its semicircular layout (see Figure 3).

Age of subglacial meltwater floods

Based on the established age of the moraines of the recessing Eire Lobe and the fact that they have not been affected by the floods, it was suggested that the Ontarian Event occurred sometime before ~ 19.6 ka ago (Munro-Stasiuk, Fisher, & Nitzsche, 2005). There is little information that would allow a fairly accurate dating. All that we know is that the moraines generated by the Algonquin Event are dissected by erosion channels attributed to the Ontarian event (Shaw & Gilbert, 1990). Using coral reef drowning episodes, Blanchon and Shaw (1995) estimate the age of the Lake Livingstone Event at 14.2 ka. Tarasov and Peltier (2006) dated *meltwater pulse events* using a complex series of data, including $\delta^{18}O$ time series from the Greenland Summit ice cores (Johansen et al., 2001), Heinrich events, and ^{14}C dating of marine sediments, as well as sediments in the Mississippi delta. All were interpreted as elements influencing the formation of the North Atlantic Deep Water, part of the global thermohaline ocean circulation, the "engine" that drives climate on the planet (Rahmstorf, 2006). Although the authors favoured northwest drainages into the Arctic Ocean, they suggest a possible age of a southern drainage around 10.7 ka ago.

Flow estimates

Given the pioneering stage of this model, and the scarcity of field and lab data, quantitative flow data for these flood events is rare and highly estimative. Beaney and Hicks (2000) have estimated (based on erosional features) discharges for the Lake Livingstone Event in the order of $10^6\,m^3/s$. The detailed analysis of the Glacial Grooves State Memorial (whose formation is attributed to the Ontarian Event) has allowed estimates of a flow width of 30 km, with an average thickness of 2 m (although there is evidence in the field that it could reach 18 m), and a speed of 5 m/s (within the same order of magnitude with the Lake Livingstone Event), enough to drain the whole of Lake Erie in one year (Munro-Stasiuk, Fisher, & Nitzsche, 2005). Such massive storage of water upflow should not come as a surprise, given the immense volume of meltwater detected underneath the Antarctic Ice Sheet (Perkins, 2006).

It is often argued that sheetflow is unstable and rapidly breaks down to channelized flow. In fact, this is one of the main arguments used against the meltwater flood hypothesis. Shoemaker (1991, 1992, 1994) has, however, provided theoretical arguments in favour of persistent sheetflow. Recorded events also confirm that. The sheetflow during the Icelandic jökulhlaup of 1996 was maintained for tens of hours (Russell & Knudsen, 1999).

Erosional Features on the Niagara Escarpment

Scouring marks

The Niagara Escarpment caprock has preserved many surface scouring marks of which the s-forms (bedrock sculpted forms) are the most characteristic. They can be grouped according to geometry (which often reflects genetic conditions):

(a) Linear erosion forms and cavettos (Kor, Shaw, & Sharpe, 1991; Shaw et al., 2000) range from small-scale striae to furrows hundreds of meters long and rock drumlins.
(b) *Sichelwannen* and comma forms (Shaw & Sharpe, 1991; Shaw et al., 2000), and transverse troughs.
(c) Multiple crescentic trough forms.
(d) Hairpins (reversed u).
(e) Potholes and *müschelbruche*.

Aerial images reveal spectacular linear forms (furrows and rock drumlins), as well as crescentic (hairpin) ones on the extensive offshore shoals of northwestern Bruce Peninsula (Kor & Cowell, 1998). Their scale varies from several meters to hundreds of meters (especially the straight furrows), being much less visible on land (heavily forested). Similar features are present on the northeastern corner of the Georgian Bay, in the French River area, in metamorphic terrains (Kor, Shaw, & Sharpe, 1991), and also south of the Canada–US border in the world famous Glacial Grooves State Memorial on Ohio's Kelsey Island. Linear erosional forms have also been discovered on the bottom of Lake Erie (Munro-Stasiuk, Fisher, & Nitzsche, 2005).

A special type of erosional marks is worth mentioning in the wider context of glacial erosion. Incipient tunnel channels are usually cut in till deposits, with meandering paths and transverse ridges. They have been described from east-central Alberta and south-central Michigan (hence in the general Niagara Escarpment area), and are also interpreted as subglacial features (Sjogren, Fisher, Taylor, Jol, & Munro-Stasiuk, 2002).

Valleys

Valleys are by far the most striking erosional landform along the Niagara Escarpment, as most of them cut across the scarp, sometimes creating spectacular gorges (of which the Niagara Gorge is the largest, deepest and most famous). Most of these valleys are classified in what one could call "classical" geological and geomorphological literature as *reentrant* valleys, that is, incised in some pre-glacial period, filled with glacial till, and then reopened by post-glacial erosion (Tovell, 1992). Others, however, attribute these valleys and many other forms to subglacial catastrophic sheetflow (a euphemism for "floods") (Kor & Cowell, 1998; Shaw, 2002). They point out that most of the reentrant valleys are consistently aligned, which suggests formation by one event. Moreover, all along the Georgian Bay, the deepest sections systematically coincide with the center lines of reentrant valleys along the escarpment. Kor and Cowell pointed out that the average bearing of the reentrant valleys on the eastern side of the Bruce Peninsula coincides with the average bearing of the s-forms on the western side of the peninsula (Figure 3).

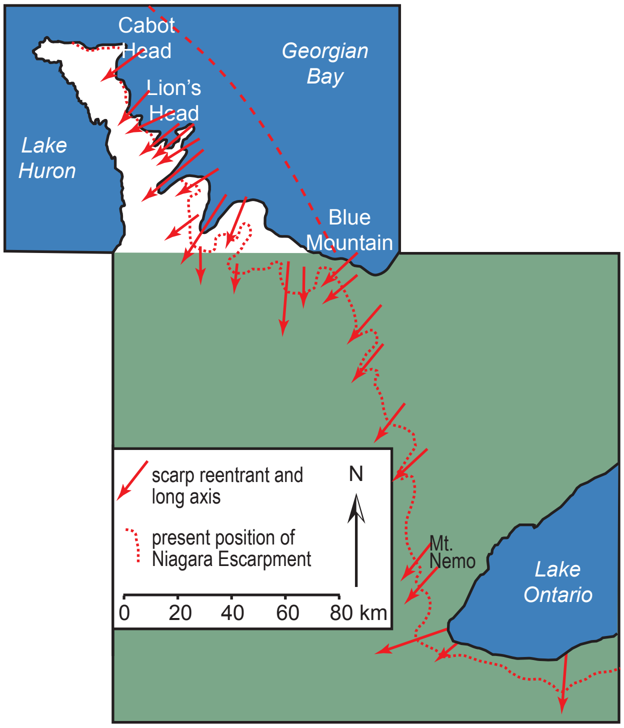

Figure 3. Schematic map of the Canadian segment of the Niagara Escarpment with the main reentrant valleys and the postulated position of the escarpment before the sheetflood event (From Kor & Cowell, 1998). This author does not believe there existed an escarpment before the sheetflood (see text)

Potholes

General discussion

Although quite spectacular, potholes have received relatively modest interest from the scientific community. Kayser (1912) was the first one to make the distinction between (1) fluvial potholes, (2) glacial potholes, and (3) marine potholes. Later Rehbock (in His-Lin Tschang, 1969) was probably the first to investigate pothole formation in the laboratory. He identified two types of water current/flow that can be involved in pothole formation: (1) eddies with vertical axes, and (2) water rollers with horizontal axes. Hsi-Lin Tschang dedicated a good part of his Ph.D. thesis to the subject of the geomorphological study of potholes. There are two main mechanical types of water erosion that create potholes according to this author: (a) toolless water, termed "hydraulicking," and (b) tool-bearing water, termed "abrasion." It is worth mentioning that the author above makes no reference to cavitation, although that has been reported by many authors (Austin, 1994; Beaney & Hicks, 2000; Dahl, 1965; Munro-Stasiuk, Fisher, & Nitzsche, 2005; Shaw, 2002) in the context of high-velocity flow.

As a geomorphic type, potholes are believed to represent indicators of high-velocity channelized drainage. They are formed by swirling water carrying coarse hard sediments. This is why potholes are a very important geomorphic feature in assessing meltwater sheetflow conditions.

Potholes are normally found in riverbeds, or on the walls of encased drainage channels. I have noticed that whenever the drainage was/is directed north or south, there is a marked tendency of potholes being more frequent on one side of the channel, due to the Coriolis forces. Cave passages sometimes display quite spectacular potholes. In rare cases they have reversed gradients, having been excavated towards the upstream rather than vertical, sideways, or downstream as in the case of surface potholes. There seems to be no specific literature dealing with this particular topic (reversed gradient potholes in caves), but from personal experience I have noticed that these always occur on the floor of passages that bear clear signs of under-pressure (full conduit) drainage. The walls of such cave passages are usually sculpted into many scallops, which are in this case the result of turbulent flow and dissolution of the limestone (Ford & Williams, 1992). It seems therefore reasonable to assume that such potholes associated with s-forms could be used as indicators of confined, under-pressure drainage.

When occurring on the lee side of resistant obstacles to turbulent flow (hence usually on higher grounds) in association with extensive s-forms on bedrock surfaces, potholes can be interpreted as indicative of catastrophic flood release of meltwaters beneath an active ice sheet (Kunert & Coniglio, 2002; Shaw, 2002). This confirms the similarities with the aforementioned karst conduits.

In some cases, potholes can form without a significant contribution of high-energy flow. On the very summit of the granitic monolith known as the Enchanted Rock in Texas, I have found many small to medium size, shallow potholes (in most cases aligned) formed by a combination of tectonics, chemical alteration of granite by phitocorrosion, and temporary runoff.

Potholes on the Niagara Escarpment

Potholes are present all along the Niagara Escarpment and even in the adjacent metamorphic terrains, from French River in the northeastern corner of the Georgian Bay to the southwestern corner of the Algonquin Park (Figure 4), well into the Canadian Shield. Also on the shield, Gilbert (2000) describes a pothole northeast of Lake Ontario, in paragneisses. Its location on a high ridge precludes formation by modern subaerial stream flow, confirming subglacial flow (from northeast to southwest according to Gilbert).

In the southern section of the Niagara Escarpment, proper potholes are rare, but downstream dissected bowl-shaped hollows are associated with virtually all the waterfalls cut on the rim of the scarp. The caprock (Lockport Dolostone) is much thinner than further north, and the underlying softer sedimentary sequence of the Cataract and Clinton Groups (Tovell, 1992) is well exposed. It is possible, in my view, that at the origin these were massive potholes eventually dissected downstream, when the transition from conduit to free-face flow occurred.

In the central section, potholes tend to appear grouped in certain areas on the thicker, more massive Amabel Dolostone.

In the north, on the Bruce Peninsula, potholes are also grouped, with the highest frequency on the eastern side (close to and right on the brow of the escarpment), and on the northwestern rocky corner of the peninsula (Figure 3).

I have identified three basic geometries of potholes:

(a) cylindrical, preserving their average diameter from top close to bottom, which is usually concave;(
(b) conical, larger at the top and gradually narrower towards the bottom, which can have many different morphologies; and
(c) bell-shaped (or inverted cone), with the bottom wider than the opening, their bottom being usually convex.

As the glacio-fluvial origin of the potholes was not in question, I have adopted a simplified parameter

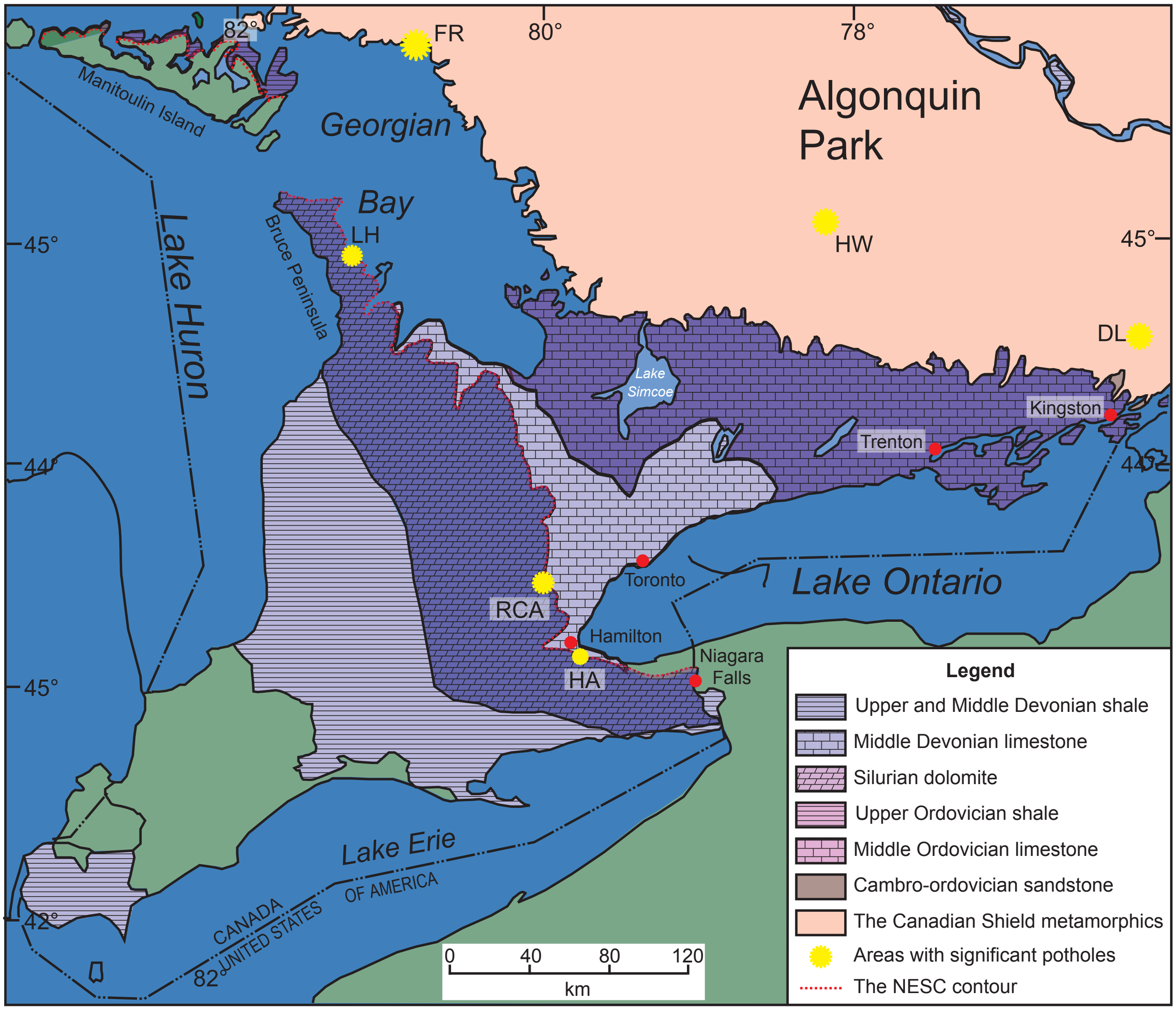

Figure 4. Map and geology of south-western and central Ontario with the location of the areas with potholes investigated in this study. HA = Hamilton area; RCA = Rockwood Conservation Area; LH = Lion's Head; FR = French River; HW = Harburn Wells; DL = Devil's Lake.

of pothole geometry: V = W/D, that is, width (of the opening) over depth. This has allowed the separation of three types: "deep" (V < 1), "even" (V ≈ 1), and "shallow" (V > 1). Henceforth I will be using the three types in italics.

1. Harburn Wells

Located east of the village of Harburn, Ontario (N45°07'27.4", W78°23'56.0") on a small slope cut in metamorphosed granites, there are eight cylindrical, *deep* potholes, all vertical, with diameters varying from 1 m to 3.5 m. The deepest reaches 5 m below its upper rim (Figure 5). There is a very small v-shaped valley that ends on the edge of the slope. East of the slope there is a fairly flat-bottomed depression. One of the potholes bears evidence of neotectonics, its mouth being slightly shifted by a small fracture line.

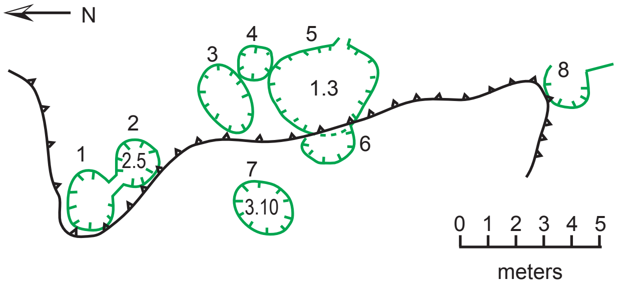

Figure 5. Sketch of the Harburn Wells (see text).

None of the existing features allows identification of the direction of water flow when the potholes were formed. It is possible that, like in the case of the French River potholes (Kor, Shaw, & Sharpe, 1991), the flow was uphill, over the slope. The neotectonics affecting one pothole seems to indicate excavation below the ice cap (whose melting probably led to the rebound that could have induced neotectonics)

2. Rockwood Conservation Area

Located near Guelph, Ontario, this is one of the most spectacular "potholed" areas. Dozens of potholes are grouped here within a narrow outcrop of the dolostone in what is a wide (compared to its depth) gorge with vertical walls (Figure 6). Other potholes are present further upstream along the Eramosa River. The size of the potholes varies from <1 m to 15 m. The largest (in volume) pothole at Rockwood Conservation Area is the Devil's Well (10 m deep, 5.5 m in diameter), situated 15 m above the Eramosa River (Kunert & Coniglio, 2002) (outside and northwest from Figure 6). The largest, all *shallow* potholes are generally located at higher elevations, usually on horizontal surfaces which resemble a terrace, the smaller ones close to the river in what could be considered a later-stage drainage channel. Many of the large *shallow* ones are dissected by the present slope. A very interesting pothole is located on the top of the ridge that separates two converging erosion channels with symmetrical cavettos, a couple of meters above the present level of the river (see below). This is one of the few potholes I have surveyed that has a clear reversed gradient pointing upstream, its axis being tilted 75° east-northeast. This is of course assuming that the present direction of the drainage (northeast–southwest) was the same when the potholes formed (which the distribution of the potholes and cavettos suggests). From what is visible from its mouth to the pond on its bottom (which corresponds to the water table), this is mostly a *deep* cylindrical pothole, although a different morphology may be present below the water.

Erosion channels with cavettos are relatively frequent, the most spectacular ones close to the river and converging into a large, dissected pothole formed by coalescence of two adjacent potholes (Figure 6). There is little doubt they began as a series of potholes that were eventually dissected and connected through drainage channels. This is consistent with a transition from a high-velocity sheetflow to a channelized flow, confirmed by the location of the large, *shallow* potholes at higher elevations, and the significantly smaller, *deep* ones at lower elevations.

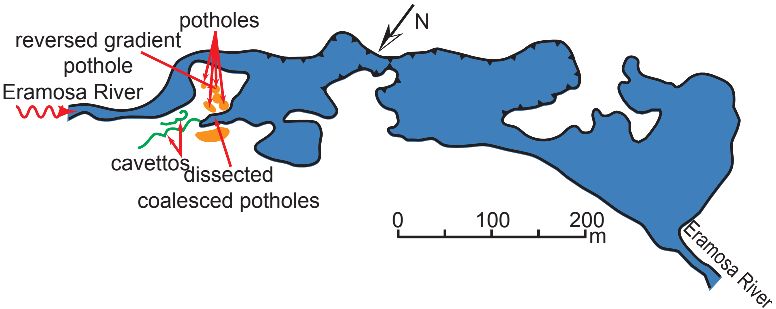

Figure 6. Map of Rockwood Conservation area—the western part. Not all areas with potholes are marked. Many more potholes are located in the eastern part, on flat sections.

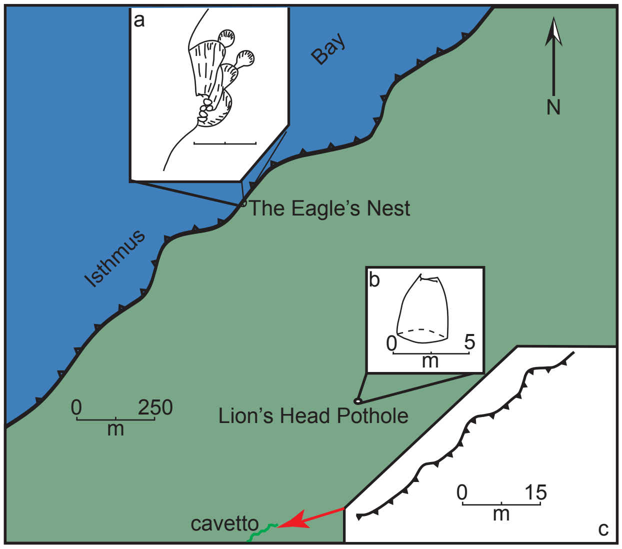

Figure 7. The Lion's Head area: (a) The Eagle's Nest potholes on the brow of the escarpment; (b) The Lion's Head Pothole is cut in an inland outcrop of Amabel Dolostone with a nearly-perfect bell shape and a side opening caused by slope erosion; (c) Cavetto with potholes (the scale of the potholes is slightly exaggerated to fit the size of the figure. Their real depth is 1.2 to 2 meters.

3. Lion's Head Peninsula

The highest density of potholes on the entire Niagara Escarpment is reached here (Kor & Cowell, 1998). Some cavettos are placed at almost regular distances along erosion channels (Figure 7). The Lion's Head Pothole (N45°00'00.8", W81°13'45.4"), located about 200 m inland from the brow of the escarpment, is the most perfect example of a *deep* bell-shaped pothole I have ever seen. The oval-shaped opening (190×100 cm) is located on the top of a vertical wall. The oval-shaped bottom (220×200 cm) is 470 cm below, and can be reached by a lateral opening at the foot of the wall. The Eagle's Nest (N45°00'06.5", W81°13' 51.2") is carved in the very brow of the escarpment, reaching over 10 m of depth. In fact, there are five coalesced, very *deep* cylindrical potholes with large (some over 50 cm), highly rounded, egg-shaped (hence the name) crystalline boulders lying on the bottom. What is unusual about these potholes is that their bayward side is almost entirely missing, which makes the pothole contour a semicircle. A circular contour is only present toward the bottom of the potholes (where the "eggs" are lodged). In the immediate vicinity many similar deep cylindrical potholes are carved in the escarpment. The pothole walls are generally smooth, with large sculpted spiral forms. At the foot of the escarpment here, extending along most of the Isthmus Bay, there is a massive boulder field consisting of highly rounded, allochthonous (Precambrian) large boulders. They often display crescentic scars (percussion marks), a clear indication of energetic water transportation.

The morphological consistency and frequency of these potholes, as well as their marked morphological dissimilarity with nearby, inland (complete) potholes (except for the ones in the walls of the erosion channel in Figure 7), suggests they were carved into the vertical (sometimes even overhanging) escarpment, rather that being secondarily dissected by slope recession. If so, a flow from inland and over the escarpment into Isthmus Bay (Figure 7) could not have produced such open potholes; a reversed flow, from the bay inland, could.

The time element in pothole formation

Although it has been inferred (His-Lin Tschang, 1969; Kor & Cowell, 1998) that potholes form quickly, there is very little published about direct time measurements. A very interesting paper (Viswas & Veena, 2004) presents clear evidence that *deep* cylindrical potholes (the largest has an opening of 110×80 cm and a depth of 129 cm) formed inside man-made channels cut in massive basalt about 60 years ago. It is remarkable that, given the use of these channels (diverting waters from the Indrayani River to a nearby masonry weir), one can assume the flow through the channels was significantly turbulent only during flooding periods, when the channels have actually increased turbulent flow. Munro-Stasiuk, Fisher, & Nitzsche, (2005) suggested a drastically shorter time for the formation of some of the s-forms at the Glacial Grooves State Memorial, namely, days or weeks. These examples clearly point out that turbulent flow, even on very hard substrate, can create s-forms in a very short time.

Discussion

The unusual quasi-semicircular shape of the Niagara Escarpment recalls the *sichelwannen* and hairpin scouring marks found along it, with which it shares general bearing, pointing to a northeast-southwest flow. This is consistent with the average bearing of most linear features, including reentrant valleys. This is further consistent with a catastrophic meltwater sheetflow in one coherent event that could have eroded the assembly of what we now call the Niagara Escarpment. Given the flow estimates mentioned above, which are more on the moderate side, there was enough hydraulic energy available to back-strip large areas of the caprock.

According to preliminary field data (Fulton, 1989b), it is likely that the Michigan Basin's sedimentary sequence continued across the Canadian Shield to the James Bay area, which means that today's basin is but a remnant of a vastly larger sedimentary area that once covered most of the Ontarian segment of the Canadian Shield. Regional rebound triggered by the melting of the Laurentide Ice Sheet resulted in fracturing of the caprock in the highest areas. This fracturing may have been bolstered by pre-existing subglacial karst drains, and cave systems similar to Castleguard Cave's upper segments developing underneath the Columbia Ice Field (Ford & Williams, 1992). The rebound further triggered massive subglacial water displacement, which eventually resulted in subglacial meltwater sheetfloods. If a part of the sheetflow penetrated through the fractures and subglacial karst, the water could have reached the soft, non-carbonate sediments below the caprock, rapidly eroding them. This, in turn, would have caused massive plucking of large slabs of the caprock, and consequently an accelerated recession (back wasting) of the entire sedimentary sequence covering the shield's metamorphic terrains.

The further away from the water storage area the sheetflow got, the lower its energy, and the "erosion front" eventually stopped roughly where the Niagara Escarpment is today. The turbulent sheetflow running over the edge of the newly-formed escarpment rapidly excavated opened potholes on the brow, and closed ones, erosion channels and cavettos further inland. The Lion's Head location described above is a good example in this context, the Eagle's Nest being excavated by the waters running from the Georgian Bay over the brow of the escarpment. The coarser sediments settled at the foot of the escarpment (where the highly rounded boulder fields are located today), while the fine ones were spread out beyond the escarpment, far inland. The advanced roundness of the large boulder fields, the frequent percussion marks and their exclusive metamorphic origin, proves a long and high-velocity transport, consistent with the sheetflood model. Turbulent sheetflow combined with tectonics induced by the rebound can explain the excavation of the reentrant valleys (Figure 3).

The presence of the reversed gradient pothole at Rockwood Conservation Area and its location at a lower elevation is evidence that both the upper, wider channel and the lower drainage channels were cut by sheetflow. The flow here was from east-northeast to west-southwest, consistent with Kor and Cowell (1998) and the Ontarian Event. If sheetflow was maintained this far south from the storage area, it is possible that the area where it broke down into channelized flow was Lakes Ontario and Erie.

Gilbert's (2000) proposed flow direction (northeast-southwest) assigns this feature to the Ontarian Event, and places it within the same major drainage path on which the Glacial Grooves State Memorial is located, that is, along Lakes Ontario and Erie (for which I tentatively propose the name "Onterie Channel").

As for the preceding Algonquin Event (Shaw & Gilbert, 1990), since its north-south drainage roughly coincides with the long axis of Georgian Bay and approximately that of Lake Michigan, it is possible they too have been excavated (at least in part) by this catastrophic meltwater sheetflow. If so, it could have influenced the way in which the subsequent Ontarian Event flow was directed.

Based on the above, one can assume that the formation of the Niagara Escarpment was essentially catastrophic, with minor local postglacial adjustments through mechanisms like the ones invoked by Tovell (1992, pp. 77–79) and Heinz (1997).

The assembly of subglacial erosion features plays a major, if not determinant, role in the subsequent subaerial development of the landscape. The uniformitarian timeframe proposed for the Algonquin and Ontarian events, although far from being considered certain by the proponents, place them in the final stages of the Ice Age, which according to young earth creationist models (Oard, 1990) is post-Flood. Because of that, it is quite possible that initially the Laurentide Ice Sheet covered a significantly higher energy landscape (created during the recessive phase of the Flood) than what one can see today. In this case, given the massive levelling of the central North American continent, the subglacial erosion must have been considerably more active and rapid than estimated, which would further confirm the subglacial formation of the Niagara Escarpment.

Englacial karst hydrology in ice deposits

There is one other aspect that needs to be considered with subglacial meltwater floods, and which does not appear to have been a major concern for most of the authors I consulted: what happened to the suprajacent ice? High-velocity subglacial water displacement must have seriously affected the ice. For one thing, all loose blocks of ice would have been rapidly removed and transported away. Present-day fragmentation of continental ice sheets is generally attributed to ice flow (uneven bedrock), tectonics, and earthquakes (Davis, 2007). The large amounts of subglacial meltwater mentioned throughout the present paper suggest another major source of glacial fragmentation. As mentioned before, Shaw has proposed that glacial sediments like drumlins accumulated between the bedrock and melt hollows on the bottom of the ice (Shaw, 2002). Shaw, however, has not dealt with the extent of such melt hollows inside the ice (englacial cavities).

The existence of karst-like features in ice deposits, thermokarst or more accurately thermopseudokarst (Silvestru, 1990), has been recorded for a long time. The Saint Gervais catastrophe in 1892 at the foot of Mont Blanc in France has given water circulation in glaciers (through karst-like conduits) a new and frightening dimension—175 people were killed by the catastrophic drain of an estimated 200,000 cubic meters of water released from an elevation of over 3,000 m underneath the Tête-Rousse Glacier (Catastrophes, n.d.). It was, however, through the advent of extreme exploration inside glaciers that the true extent and similarities with orthokarst were revealed (Benn & Gulley, 2006; Davis, 2007). Benn clearly states, after having surveyed nearly 3 km of englacial cave passages in the Himalayas:

> Indeed, we found that current glacial hydrological theory is inadequate in almost all respects to explain the characteristics and distribution of the caves, and that karst hydrology provides a much more powerful theoretical framework (Benn & Gulley, 2006, p. 14).

What he essentially refers to is the existence of a karst-type aquifer throughout massive ice deposits which would behave in similar ways.

Another, somewhat more complex type is the subglacial thermopseudokarst, like the one in Iceland, which is connected to the surface through massive shafts created by steam from geothermal vents, but also through an intricate network of englacial conduits (Sjogren et al., 2002; Vander-Molen, 1984). Such a superposition would increase the amount of water circulating through the ice and extend the network of conduits, because warm water and air is added to the system.

It is quite possible that subglacial volcanic activity has also played a role in melting the ice and possibly triggering subglacial floods. I have found interesting clues to this in the Lower Mainland British Columbia. Rounded gravel is distributed on wide areas, oftentimes on high ridges, and percussion marks on some boulders seem to indicate energetic subglacial transportation. Near the Indian's Head in Summerland BC, the same gravel is incorporated in a volcanic agglomerate, which confirms subglacial eruptions in the recent past. One can reasonably argue that it may have been such volcanic events that triggered the massive discharges towards the south, all resulting in the Missoula Flood.

All the cases mentioned above are referring to alpine-type glaciers. Very little is known about similar features in the ice sheets. It has been shown that accelerated ice sheet flow in Greenland correlates well with the seasonal increase of surface meltwater reaching the base of the ice sheet (Zwally, Abdalati, Hering, Larson, Saba, & Steffen, 2002). Similar cases are presented from Alaska (Davis, 2007). I have found, however, no reference to thermal pseudokarst in the same areas, only inferences. Extrapolating the same speculations into the past, it has been proposed that similar mechanisms have accelerated the demise of the Laurentide Ice Sheet (Zwally et al., 2002). The existence of over 140 lakes underneath the Antarctic Ice Sheet, with Lake Vostok (equal in volume to Lake Michigan) lying below 4 km of ice (Perkins, 2006), suggests that similar mechanisms are at work in the coldest environment in the world.

Orthokarst similarities and dissimilarities

Karst terrains have a clear vertical zoning, which simplified consists of an infiltration (percolation) zone and a flooded (saturated) zone (Bakalowicz, 1977). In englacial pseudokarst this zoning should also be valid, with most of the ice block/sheet acting as an infiltration zone, and the base of the ice as a saturated zone (except for areas where free-flow does occur between the base of the ice and the bedrock). Exploration inside the ice though (NOVA, 2004) has revealed another similarity with karst terrains: clogged passageways can temporarily flood some sections. However, in the case of alpine glaciers, this clogging is periodic, being caused by the overnight freezing of most stagnant water (in sumps, that is, more or less u-shaped, permanently flooded passages) inside the glacier as surface supply ceases through the night. When daytime meltwater supply resumes, it often causes further flooding until the clogging is eliminated and global flow restored. The fact that the final discharge (outlet) of meltwater does not seem to significantly diminish through the night suggests the supply and storage of liquid water at the foot of glaciers is considerable.

Glaciology has not specifically dealt with the morphology and spatial distribution of drainage systems through glaciers. It appears that in most cases a rapid vertical descent through shafts is assumed (NOVA, 2004). While this may be true in thinner ice, vertical shafts over kilometres of ice (like in Greenland and Antarctica) seem to be an unreasonable assumption. It is most likely that the similarity with karst drainages applies here too, shafts being connected by extensive subhorizontal or sloping passages. The existence of horizontal or inclined meandering passages inside the Ngozumpa Glacier in the Himalayas (Benn & Gulley, 2006) confirms this. The extent of such passages is unknown, because there are no proper karstological studies in such environments. But given all the above, there is no reason why they cannot be extensive. Unlike orthokarst though, passages in ice can be rapidly closed by the continuous movement of the ice, leaving “scars” which would weaken the ice just as tectonics does. These are permanent closures. Annealing can also close many passages in winter time, but these should be mostly periodic closures (Ford & Williams, 1992, p. 475). New passageways would constantly be created to drain the meltwater towards the base of the ice.

Many high alpine cave systems like Hölloch (over 193 km long) and the Siebenhengste-Hohgant System (over 155 km long) in Switzerland, or Castleguard in Canada (over 20 km long) (Gulden, 2008), are repeatedly flooded from below, by waters ascending through the passageway network during summer floods. I have seen clear evidence in Hölloch that the flooding can reach over 100 m above normal levels. All these cave systems have a significant vertical extension (extended passages following moderate to steep bedding planes), and when flooding occurs (during rainy periods) the limited discharge capacity at the lower end causes waters to rise into the available cavities upstream. Sometimes the hydraulic pressure can be so high as to lift and transport large boulders vertically up. I have seen in many instances conical sediment piles (usually a mixture of gravel and sand, but also the odd 10 to 15 cm cobble) around narrow shafts connecting various levels of a cave. This sediment came from lower levels of the cave. Given the above, one can confidently assume that the same kind of flooding, with similar consequences can occur inside glaciers (both alpine and continental) if the conditions are right.

The subglacial flood hypothesis and the karst connection

If subglacial water pressure reached values high enough to trigger catastrophic subglacial sheetflow over a front of 30 km, the effect of such flow and pressure on existing englacial pseudokarst could have been devastating. Water would ascend at high-velocity through most of the voids, bursting (if the ice was not very thick) to the surface of the ice sheet and carrying with it subglacial sediment. As hydraulic pressure increased inside the ice, rupture could have occurred and rapid fragmentation of the ice followed, especially at the periphery where the pseudokarst conduits would be bigger as they reached the bedrock. The resulting blocks (some of very large size) could have been detached and transported by hydroplaning for some distance, especially where the sheetflow was thick enough. Even if they touched the bedrock, once displaced and in the middle of the flow, they could have been dragged, causing scouring marks which in some cases could be inconsistent with the ice-flow direction. Another possible consequence could be the formation of ice dams further downflow, and the subsequent accumulation of lakes. Massive accumulations of ice blocks would have most probably occurred at the foot of the newly-formed escarpment, protecting most of it from channelized flow incision.

It is possible, in my view, that in some areas this protective ice-block shield was missing or less efficient, especially where the narrow reentrant valleys have been excavated. This could have accelerated valley incision.

The above hypothesized mechanism could have significantly accelerated deglaciation. Others have already mentioned this possibility without invoking glacial pseudokarst. Based only on the possibility of increased meltwater input through the ice, and the ensuing additional lubrication of glacier base, Zwally et al. (Goddard Space Flight Center, 2002; Zwally et al., 2002, p. 221) suggested that "Enhanced basal sliding from surface meltwater may have contributed to the rapid demise of the Laurentide Ice Sheet …" Rapid deglaciation at its turn would have increased the rebound of the bedrock, and through that, damming of subglacial water in the areas still covered by ice. This could have increased the incidence of outbursts of meltwater as subaerial, more localized floods, further complicating the already complex erosional features that cut through glacial deposits.

The young-earth timing of the subglacial meltwater sheetfloods

The Quaternary timing of the Algonquin and Ontarian events presented above is based on standard long-age records whose credibility and accuracy has been discussed extensively before. I will therefore not deal with it, but simply try to look for an alternative.

From a technical point of view, the main element that controls the frequency of subglacial meltwater floods is the input of meltwater from the surface. This, in turn, is a function of surface temperature and the efficiency of transfer of meltwater from the surface to the bottom of the glacier, which is dependent on the extent of englacial pseudokarst.

Zwally et al. (2002) present only a correlation between the periods of surface melting and the acceleration of ice flow. No quantitative (volume of meltwater) data is presented. Satellite imagery has allowed estimates of surface meltwater ponds on ice caps in Svalbard and the western margin of Greenland Ice Sheet (Sneed & Hamilton, 2006). Thus in an area of ~172 km^2 of the latter, a volume of 3.7×10^7 m^3 of meltwater was calculated for August 2005. This is one order of magnitude higher than the per-second discharge estimated for the Ontarian Event in the Lake Erie area only (see above). So the volume of water accumulated on 172 km^2 of the Greenland Ice Sheet during one summer month would sustain that sheetflood for 10 seconds.

Using map 1703A (Fulton, 1989a) (showing the extent of Laurentide Ice Sheet at 18 ka BP), and the limiting factors of meltwater productivity in the context of this paper, that is, the proposed Trans-Laurentide Ice Divide, the dome structure and the edges of the ice sheet, all of which would have facilitated water drainage towards the same storage area, I estimated (using the lowest end of the estimates) the "productive" ice sheet surface at approximately 2.6×10^6 km^2. Assuming the meltwater yield from the Greenland Ice Sheet (2.15×10^5 m^3/km^2) and similar climate conditions, the monthly meltwater volume could have reached 5.59×10^{11} m^3. This is one order of magnitude more than Lake Ontario (4.4×10^{10} m^3) (Great Lakes Information Network, 2006). One can, of course, make many adjustments here, including the amount of meltwater that flowed over the edge of the ice sheet, but I believe even the most conservative estimates would allow for very short periods of time (years, maybe decades) for enough subglacial meltwater storage to trigger catastrophic sheetfloods. In fact, one can even affirm that such releases were inevitable and periodic in order to balance meltwater budget within, and throughout, the ice sheet when post-glacial melting started. Although no similar surface meltwater estimates for the Antarctic Ice Sheet were available to me, I would venture to assume volumes within the same order of magnitude. That would allow for lakes like Vostok to have accumulated in very short periods of time too. Hence, periodic catastrophic subglacial meltwater sheetfloods like the one that created the Labyrinth (Lewis et al., 2006) could be confidently postulated for Antarctica.

Conclusions

The Niagara Escarpment is an unusual semicircular cuesta that cannot satisfactorily be explained by classical, slow-paced geomorphic processes. Extensive erosional features along it, including potholes, linear, curved, and crescentic s-forms and reentrant valleys are consistent with a northeast to southwest water, rather than ice flow. Furthermore, the general layout of the escarpment—a semicircle opened towards the south-southwest—roughly coincides with the axis of most linear and crescentic s-forms, which suggests the same northeast to southwest flow as the possible cause of the unusual shape of the escarpment. There is increasing evidence, and a growing group of scientists studying it, that points toward catastrophic subglacial meltwater sheetfloods as the source of the erosion marks, and implicitly, the escarpment. Two consecutive such events, the Algonquin and Ontarian, have been hypothesized, with the latter probably creating most of the escarpment.

The study of potholes along the escarpment, particularly the existence of reversed gradient ones, have allowed the tracing of subglacial sheetflow (with all the space between bedrock and the bottom of the ice sheet filled with water flowing at high pressure) as far south as Guelph, which would project the channelized flow area further south, in the area now covered by Lakes Erie and Ontario. The spectacular s-forms in the Glacial Groove State Memorial on Lake Erie's Kelsey Island (Ohio) are excellent proof of that.

Subglacial meltwater sheetfloods had a major effect on the suprajacent ice sheet too. Not only has ice flow accelerated because of increased lubrication, but the high pressure of the water could have caused invasion of the extensive englacial pseudokarst that drained surface meltwater toward the base of the ice sheet, and caused rupture and fragmentation of the ice. This may have significantly increased the pace of deglaciation, resulting in increased rebound of bedrock and possible damming of subglacial meltwater. This could have caused periodic outbursts of meltwater and more catastrophic erosion, with the Niagara Escarpment—already in place by this time—playing the role of deflector.

These Late Glacial—Early Post-Glacial catastrophic subglacial flooding events required volumes of surface meltwater that the Laurentide Ice Sheet could have produced (given present-day estimates in Greenland) in years, maybe decades. This raises the possibility that such events were recurrent, maybe even periodic. The implication is that landscape erosion in Ontario (and elsewhere where the Laurentide Ice Sheet was active), including the Niagara Escarpment, unfolded in paroxsytic episodes, rather than through slow processes covering hundreds of thousands of years as mainstream geology claims. This means one can presume a fairly varied pre-glacial landscape, which one would expect after the recession of the Flood waters.

References

Austin, S.A. 1994. *Grand Canyon, monument to catastrophe* (pp. 104–105). El Cajon, California: Institute for Creation Research.

Bakalowicz, M. (1977). Relations entre la dynamique des eaux du karst et les processus de karstification. *Proceedings of the seventh international speleological congress, Sheffield* (pp. 10–12).

Beaney, C.L., & Hicks, F.E. (2000). Hydraulic modelling of subglacial tunnel channels, south-east Alberta, Canada. *Hydrological Processes, 14*, 2545–2557.

Benn, D., & Gulley, J. (2006). Under thin air: the 2005 Ngozumpa Glacier Caves Research Project. *NSS News, 64*(10), 1317.

Blanchon, P., & Shaw, J. (1995). Reef drowning during the last deglaciation: evidence for catastrophic sea-level rise and ice-sheet collapse. *Geology, 23*, 4–8.

Broecker, S.W. (1987). Unpleasant surprises in the greenhouse? *Nature, 328*, 123–126.

Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., & Wolfli, W. (1989). Routing of meltwater from Laurentide Ice Sheet during the Younger Dryas cold episode. *Nature, 341*, 318–321.

Catastrophes, n.d. Retrieved from http://glaciers.climat.free.fr/Catastrophes/Catastrophes.html

Cox, D. (1979). A diluvial origin for drumlins. *Creation Research Society Quarterly, 16*, 154–162.

Dahl, R. (1965). Plastically sculptured detail forms on rock surfaces in northern Nordland. *Geografiska Annaler, Series A47*, 3–140.

Davis, M. (2007, June). Slip-sliding away: Glacier erosion processes, field notes. *The Velco Polar Resources Newsletter*, 1–2. Retrieved from http://www.vecopolar.com/Files/PDFs/Newsletter06_21_07Final.pdf.

Denton, G.H., & Sugden, D.E. (2005). Meltwater features that suggest Miocene ice-sheet overriding of the Transantarctic Mountains in Victoria Land, Antarctica. *Geografiska Annaler, 87A*, 67–85.

Dow, C.M. (1921). *Anthology and bibliography of Niagara Falls* (2 volumes). Albany, New York: J.B. Lyon Co.

Ford, D.C., & Williams, P.W. (1992). *Karst geomorphology and hydrology* (p. 305). London: Chapman & Hall.

Fulton, R.J. (Ed.). (1989a). *Quaternary geology of Canada and Greenland*. Geological Survey of Canada, Ottawa a.k.a. vol. K1 of the Geological Society of North America series produced as part of the Decade of North American Geology project. Map 1703A.

Fulton, R.J. (Ed.). 1989b. *Quaternary geology of Canada and Greenland*. Geological Survey of Canada, Ottawa a.k.a. vol. K1 of the Geological Society of North America series produced as part of the Decade of North American Geology project. Map 2545.

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

Goddard Space Flight Center (2002). Retrieved from http://www.gsfc.nasa.gov/topstory/2002060greenland.html.

Great Lakes Information Network (2006). Retrieved from http://www.great-lakes.net/lakes/ref/ontfact/html.

Gulden, R. (compiler) (2008). Retrieved from http://www.caverbob.com/wlong.html.

Gupta, S. (2005). Catastrophic flooding of shelf valley systems in the English Channel. *Geophysical Research Abstracts, 7*, 10803.

Gupta, S., Collier, J.S., Palmer-Felgate, A., & Potter, G. (2007). Catastrophic flooding origin of shelf valley systems in the English Channel. *Nature, 448*, 342–345.

Heinz, D.W. (1997). Reexamination of scarp development along Niagara Escarpment, Ontario. Unpublished master's thesis, Wilfrid Laurier University, Waterloo, Ontario, Canada.

Hennepin, L. (n.d.) *A new discovery of a vast country in America*. (Reprinted in Coles Canadiana Collection, Toronto.)

Hillaire-Marcel, C., de Vernal, A., Weaver, A., Fischer, D.A., & Solignac, S. (2004). The dispersal of the 8.2 ka Lake Agassiz drainage waters into the NW Atlantic: Working hypothesis. Retrieved from http://adsabs.harvard.edu/abs/2004AGUFMPP22A..01H

Hsi-Lin Tschang (1969). A geomorphological study of the formation of fluvial and marine potholes. *The Chung Chi Journal, 9*(1), 84–106. Retrieved from http://www.google.com/search?q=pothole+formation&hl=en&rls=coms.microsoft:en-us:IE-SearchBox&rlz=1I7ADBF&start=10&sa=N.

Johansen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen H.B., Miller, H., Masson-Delmote, V., Sveinbjornsdottir, A.E., & White, J. (2001). Oxygen isotope and paleotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and

NorthGRIP. *Journal of Quaternary Science, 16*, 299–307.

Kayser, E. (1912). *Lehrbuch der geologie*, Teil I, S.354, 4, Aufl. Stuttgart.

Kindle, E.M., & Taylor, F.B. (1913). *Geological atlas of the United States*. The Niagara Folio—U.S. Geological Survey Folio No. 190.

Knight, J. (2002). Bedform patterns, subglacial meltwater events, and Late Devensian ice sheet dynamics in north-central Ireland. *Global and Planetary Change, 35*, 237–253.

Kor, P.S.G., Shaw, J., & Sharpe, D.R. (1991). Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: A regional view. *Canadian Journal of Earth Sciences, 28*, 623–642.

Kor, P.S.G., & Cowell, D.W. (1998). Evidence for catastrophic subglacial meltwater sheetflow events on the Bruce Peninsula, Ontario. *Canadian Journal of Earth Sciences, 35*, 1180–1202.

Kunert, M., & Coniglio, M. (2002). Origin of vertical shafts in bedrock along the Eramosa River valley near Guelph, Southern Ontario. *Canadian Journal of Earth Sciences, 39*, 43–52.

Leake, J. (2006). Retrieved from http://www.tomesonline.co.uk/tol/news/uk/articles648984.ece.

Levertt, F., & Taylor, F.B. (1915). *The Pleistocene of Indiana and Michigan and the history of the Great Lakes*. U.S. Geological Survey Monograph 53.

Lewis, A.R., Marchant, D.R., Kowalewski, D.E., Baldwin, S.L., & Webb, L.E. (2006). The age and origin of the Labyrinth, western Dry Valleys, Antarctica: Evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. *Geology, 34*(7), 513–516.

Lowe, A.L., & Anderson, J.B. (2003). Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica. *Journal of Glaciology, 49*, 125–138.

Lyell, C. (1845). *Travels in North America in the years 1841–42 with geological observations on the United States, Canada and Nova Scotia*. New York: Wiley and Putnam.

Lyell, C. (1873). *Principles of geology* (11th ed.) (Vol. 1, pp. 354–358). New York: D. Appleton and Co.

Miller, J.M.G. (2002). Glacial sediments. In H.G. Reading (Ed.), *Sedimentary environments: Processes, facies and stratigraphy* (pp. 425–484). Oxford: Blackwell Science.

Munro-Stasiuk, M.J., Fisher, T.G., & Nitzsche, C.R. (2005). The origin of the western Lake Erie grooves, Ohio: Implications from reconstructing the subglacial hydrology of the Great Lakes sector of the Laurentide Ice Sheet. *Quaternary Science Reviews, 24*, 2392–2409.

NOVA (2004). Retrieved from http://www.pbs.org/wgbh/nova/mtblanc/about.html.

Oard, M.J. (1990). *An ice age caused by the Genesis Flood*. El Cajon, California: Institute for Creation Research.

Perkins, S. (2006). Cold and deep: Antarctica's Lake Vostok has two big neighbors. Retrieved from http://www.sciencenews.org/articles/20060204/fob6.asp.

Rahmstorf, S. (2006). Thermohaline ocean circulation. In S.A. Elias (Ed.), *Encyclopedia of Quaternary sciences* (pp. 1–10). Amsterdam: Elsevier.

Russell, A.J., & Knudsen, O. (1999). Controls on the sedimentology of the November 1996 jökulhlaup deposits, Skeidarsandur, Iceland. *Special Publication International Association Sedimentology, 28*, 315–329.

Shaw, J. (1983). Drumlin formation related to inverted meltwater erosional marks. *Journal of Glaciology, 29*, 461–471.

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

Shaw, J. (1989). Drumlins, subglacial meltwater floods and ocean responses. *Geology, 17*, 853–856.

Shaw, J. (1994). Hairpin erosional marks, horseshoe vortices and subglacial erosion. *Sedimentary Geology, 91*, 269–283.

Shaw, J. (1996). A meltwater model for Laurentide subglacial landscapes. In S.B. McCann & D.C. Ford (Eds.), *Geomorphology sans frontière* (pp. 182–226). Chichester: Wiley.

Shaw, J. (2002). The meltwater hypothesis for subglacial bedforms. *Quaternary International, 90*, 5–22.

Shaw, J., & 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., & Kvill, D. (1984). A glaciofluvial origin for drumlins of the Livingstone Lake Area, Saskatchewan. *Canadian Journal of Earth Sciences, 21*, 1442–1459.

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

Shaw, J., Kvill, D., & Rains, R.B. (1989). Drumlins and catastrophic subglacial floods. *Sedimentary Geology, 62*, 177–202.

Shaw, J., Faragini, D., Kvill, D.R., & Rains, R.B. (2000). The Athabasca fluting field, Alberta, Canada: Implications for the formation of large-scale fluting (erosional lineations). *Quaternary Science Reviews, 19*, 959–980.

Shaw, J., Rains, B., Eyton, R., & Weisling, L. (1996). Laurentide subglacial outburst floods: Lanform evidence from digital elevation models. *Canadian Journal of Earth Sciences, 33*, 1154–1168.

Shoemaker, E.M. (1991). On the formation of large subglacial lakes. *Canadian Journal of Earth Sciences, 28*, 1975–1981.

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

Shoemaker, E.M. (1994). Reply to comments on "Subglacial floods and the origins of low-relief ice-sheet lobes" by J.S. Walder. *Journal of Glaciology, 40*, 201–202.

Silvestru, E. (1990). Propositions pour une classification litho-génétique des formes karstiques et apparentées. *Karstologia, 15*, 55–57.

Sjogren. D.B., Fisher, T.G., Taylor, D.L., Jol, M.H., & Munro-Stasiuk, M. (2002). Incipient tunnel channels. *Quaternary International, 90*, 41–56.

Sneed, W.A., & Hamilton, G.S. (2006). Determining surface meltwater pond volume using satellite imagery. Retrieved from http://adsabs.harvard.edu/abs/2006AGUFM.C21A1126S.

Tarasov, L., & Peltier, W.R. (2006). A calibrated deglacial drainage chronology for the North American continent: evidence of an Arctic trigger for the Younger Dryas. *Quaternary Science Reviews, 25*, 659–688.

Tovell, M.W. (1992). *Guide to the geology of the Niagara Escarpment* (p. 3). Ontario: The Niagara Escarpment

Commission with the Assistance of the Ontario Heritage Foundation, Concord.

Vander-Molen, P. (1984). Running the Jökulsá á Fjöllum, Iceland's wild glacier-born river. *National Geographic, 166*(3), 306–321.

Viswas, S.K., & Veena, U.J. (2004). Evidence of formation of potholes in bedrock on human timescale: Indrayani River, Pune district, Maharashtra. *Current Science, 86*(5), 723–726.

Zwally, H.J., Abdalati, W., Hering, T., Larson, K., Saba, J., & Steffen, K. (2002). Surface melt-induced acceleration of Greenland ice-sheet flow. *Science, 297*, 218–222.