FIELD TRIP GUIDE

BGS'05

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GEOMORPHOLOGY & ECOSYSTEMS

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Introduction

A series of stops on this geomorphology field trip will illustrate ecological aspects of the modern river and gorge as well as the ancient river. The ecosystem aspects will be considered very broadly, but it will become evident that enormous changes have taken place in the biotic systems operative in the gorge system over the last few thousand years – and more recently within centuries and decades. Radical changes continue with the erection of high buildings on the Canadian side.

The stops (Figure 1) provide a visual access to most of the significant reaches in the river. Figure 2, from Charles Lyell (1845) still illustrates the regional geology accurately enough to be useful as a guide.

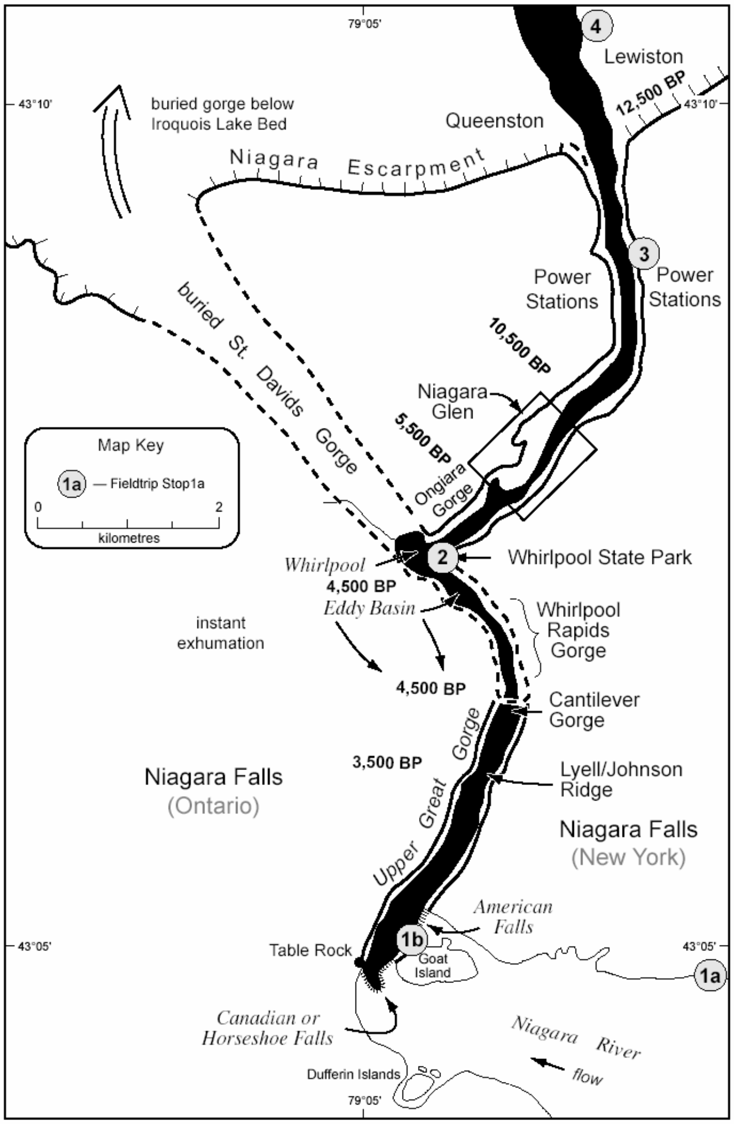


Figure 1: The main named sections of the Niagara Gorge (not all referred to in this Guide), and the approximate locations of the Field trip stops.

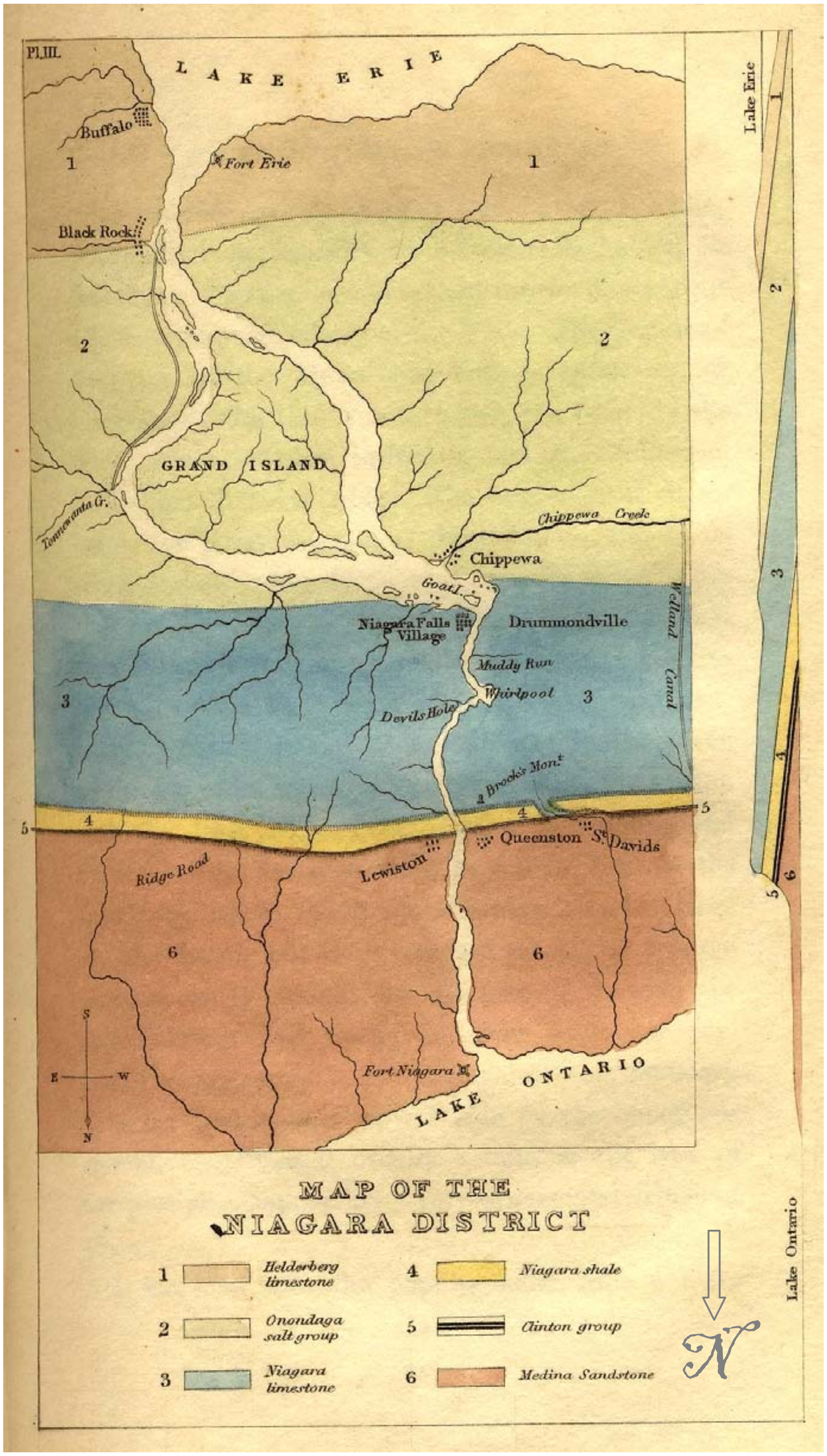
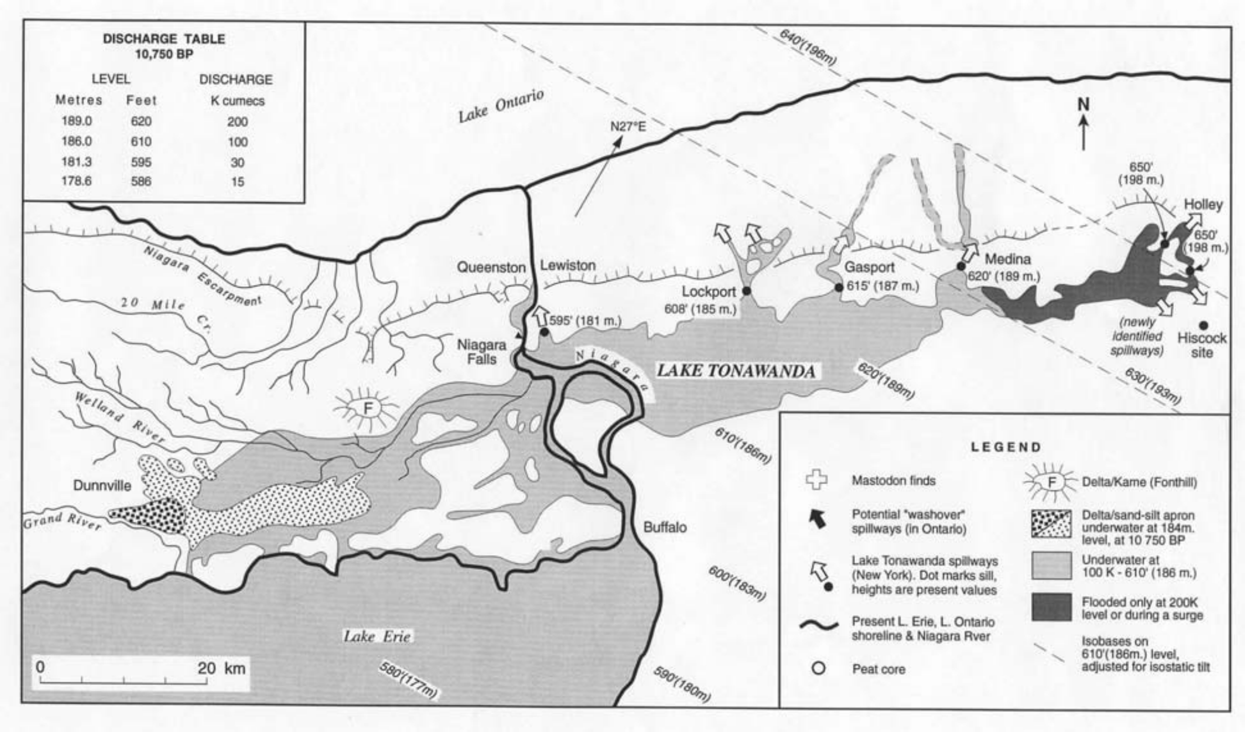


Figure 2: The first geological map of Niagara Peninsula in the Falls area (Charles Lyell (1845).

Stop 1A: Intakes for the Power Stations

We are standing in what may be called a river-lake situation with relatively shallow slowly moving water. A few millenia ago it was the site of the eastern remnants of a large shallow lake called Lake Tonawanda (Figure 3). The lake drained suddenly as the waterfall retreated into a upstream-descending rock surface. Opposite us is Navy Island, Grand Island, and the Canadian shoreline in the distance. Although the river is placid at present, winter ice developed both here in the upper river – and under natural conditions (now controlled with an ice boom) rafted in from Lake Erie - can provide a very chaotic surface, and particularly below the waterfall. Winter ice can rise to scour banks several meters above water levels – and in the lower river as much as 15 meters. Wind-sets on lake Erie can sometimes raise the lake level at Buffalo and Fort Erie by 8 feet (2.5 m) (Libicki and Bedford 1990) and are the local equivalent of floods in the river.



DISCHARGE TABLE
10,750 BP

LEVEL		DISCHARGE
Metres	Feet	K cumecs
189.0	620	200
186.0	610	100
181.3	595	30
178.6	586	15

Figure 3: Map of the Niagara Peninsula and western New York area showing the extent of former Lake Tonawanda. Notice the spillways northwards over the Niagara Escarpment, isostatic tilting eventually concentrated outflow at the Niagara Gorge before 11,500 yr BP. Lake Tonawanda was confluent with lake Erie until about 3000 yr BP.

The contemplation of power, apart from the awe at its majesty expressed by Hennepin (1678) and subsequent visitors, began about 1842 when the first measurements of Niagara River flow were made near the now Peace Bridge in the early 1840s (Blackwell and Allen, 1843). It was estimated that, in theory, Niagara Falls could power the entire industrial needs of the contemporary world. The flow estimate made on the basis of three cross-sections was 374,000 cubic feet per second (10,588 $m^3 s^{-1}$), about 87% larger than the currently accepted figure of about 5,700 $m^3 s$-^{1}. Difficulties with a slanting plumb may have led to the over-estimation.

Towards the end of the nineteenth century practical schemes to use water power to generate electricity emerged again at Niagara. One side-effect of the renewed interest was a flurry of activity to establish the rate of retreat of the Falls, taking the 1843 measurement by James Hall (1843) as a baseline. The information was clearly necessary if power stations were to be built close to the crest of the Falls. Repeated measurements were made between about 1880 and 1907 with some finality being given by the works of Gilbert (1907) and Spencer (1907) from which it was concluded that the recession rate was the order of 1.5 m (5 feet) a year. With renewed and improved measurements of discharge it was estimated that there was sufficient power for the whole of North America at the time. Discharge was determined to average 212,000,000 cfs or ~ 5760 $m^3 s^{-1}$.

The present power agreement, ratified after emergency increases in extraction during WWII, extracts 50% of the water all of the time, and 75% of the water throughout the winter, and during the night in the summer. Power feeds into the north-eastern grid system. An August 2005 announcement by the Ontario Provincial Government states that a third tunnel will be constructed to the Adam Beck Station (at a cost of nearly $1B) which will enable more efficient and continuous use of the available water allocation by 2009, and with no surface impact at Niagara.

Stop 1B: Goat Island and adjacent valley walls: Buckhorn Island State Park

We stand here on the bed of a lake – Tonawanda – that fed the Niagara River up until about 3000 years ago (Figure 3). The lake was held up by a sill – or bedrock rise – in the Niagara River at what is called the Lyell/Johnson ridge. When the sill was in existence it raised water behind it to an elevation about 3 metres higher than the mean level of present Lake Erie (175M) and that implies water depths of about 12 m (40 ft) over the bed of Goat Island where we stand. Flow through the lake would have been slow, but it would not be stagnant. Shells recovered from trenches and excavations on Goat Island and adjacent shorelines show a variety of clams and river snails.

The bed of former Lake Tonawanda is seen in the sediments of Goat Island - about 15 m of sediment can be seen from the Canadian side. Charles Lyell (1845) and James Hall (1843) found a mastodon tooth in Goat Island sediments, and Hall recognized fragments of Black Rock chert which must have been eroded from the vicinity of the river banks near Fort Erie and Buffalo.

The lake’s existence was understood by Lyell (1845) in a general way, but it was first formally mapped by Kindle and Taylor (1913) in their Niagara Folio for the USGS – straying on account of the subject matter into Canada (Plate A). They did not map the lake’s extend in Canada but mentioned in the text that it extended about ten miles west of Niagara Falls. The lake extended 100 km east as far as Holley and initially had several exits still visible as breaks and gorges over the Escarpment into Lake Iroquois below the Escarpment. Isostatic rebound tilted the lake westward so that in time outflow concentrated at the Niagara Falls and Niagara Gorge outlets.

D’Agostino (1958) is the only person known to have written a thesis or memoir on Lake Tonawanda. His account is not very detailed, and lacks for example RadioCarbon ages for molluscs, since it largely predates the period ^{14}C technology was readily available. However, he does note one significant fact – that the sections he examined indicated that the lake drained suddenly – and did not dry up slowly. Reference to contours on a modern map shows that as the Falls retreated from Lyell/Johnson bedrock ridge at a modern rate of about 1 to 1.5 m/year the crest elevation of the waterfall may have dropped 9 m (30 ft) within a period of about 100 years, this confirming D'Agostino's diagnosis. On the corner from the north side of the American channel at the American Falls there are several terraces that mark the lowering water level as the downstream sill was breached by the receding waterfall and the elevation of the waterfall crest dropped as the revealed bedrock surface dropped to the south.

On Goat Island surface molluscs were collected by Tinkler (1998) from two similar trenches - each about one metre deep. The first was adjacent to the main gorge wall and aged at 5230 ± 120 (BGS-1694). Calkin and Brett (1978) aged two samples of shells from a similar location (within a metre of the surface), and obtained 9080 ± 130 (BGS-275) and 9115 ± 215 (QC-118). The second sample was from half way along Goat Island in the up-river direction, close to the main road access, and aged at 9000 ± 180 (BGS-1693). Taking all the Goat Island near-surface ages together it is clear that they record Goat Island's sediments accumulating as bottom sediments of Lake Tonawanda until the lake drained, after 5000 BP on the evidence of the shells. However, an age of 3780 ± 90 (BGS-273) on molluscs at the Sewage Plant exposure of Lake Tonawanda sediments (Calkin and Brett, 1978) is interpreted by them to indicate that Lake Tonawanda survived until this date. (All the ages from Calkin and Brett should be increased by 360 years to ensure comparability with our dates which have had a fractionation correction of 360 years added. The adjustment is independent of age). Lake Tonawanda would have been drained somewhat after this according to Tinkler et al. (1994) who dated the breaching of the Lyell/Johnston topographic sill to the period 3500 to 3000 BP.

During its existence, Lake Tonawanda at its western end undercut the Niagara Falls moraine to produce the prominent cliff behind the parking lots on the Canadian side. Because the maximum fetch was from the east, wave action on the lake, fed by abundant fine material from the erosion of the cliff built up a barrier island complex at the base of the cliff and managed to trap the Welland River (Chippewa Creek) between the cliff and the barrier island. The incised meander of Dufferin Islands, incised as the river lowered it self to the same baselevel lowering that caused the terraces opposite Goat Island. Two points of evidence remain for this "trapped" river – now dismembered. On several maps from 1800 and before, a long sinuous pond is shown west of the present river margin and also a matching island called Cedar Island (this at a time when the river margin was not controlled as it is now). From the coloured surficial map in Kindle & Taylor (1913) – and mapped some years before this - the former course of Chippewa Creek can easily be re-constructed (Figure 4). The other piece of evidence is from Hennepin's original engraving of the waterfalls (see Figure 4). As well as the Canadian and American falls there is a prominent "tea" spout from the west. Also existing from this period (late 17C until the mid 19C was a prominent overhand called Table Rock (giving its name to the restaurant now). The overhang probably developed on the downstream side of the Chippewa channel and helped to define the "spout."

The ready availability of water has always been a driver for industry. Initially, water for industrial use was taken off the Niagara River above Goat Island, taking advantage of the pre-existing bed slope down towards the Falls. Leads took the water to Mills perched on the edge of the gorge just downstream of the American Falls. The situation at the turn of the nineteenth century is illustrated in Figure 5.

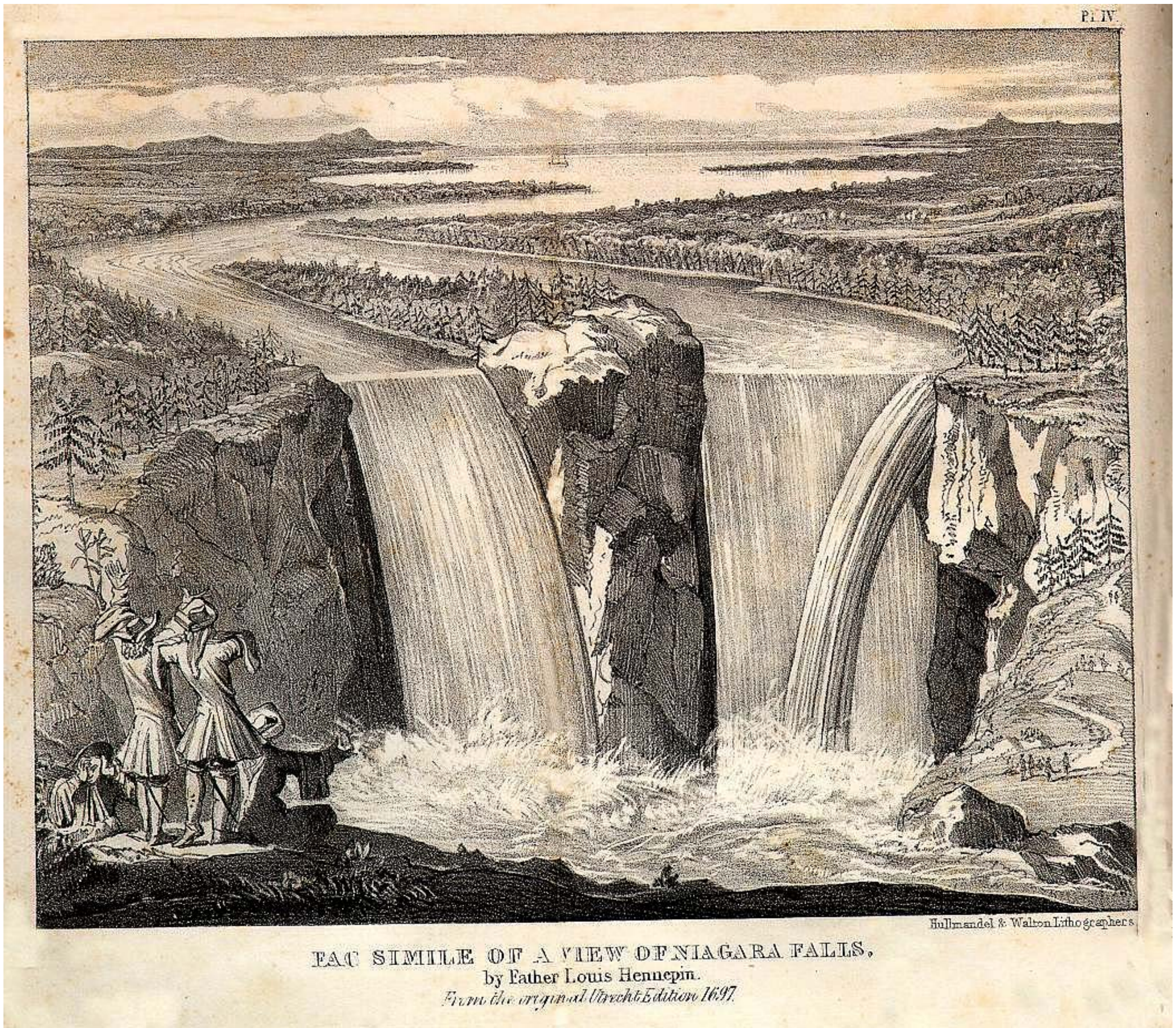
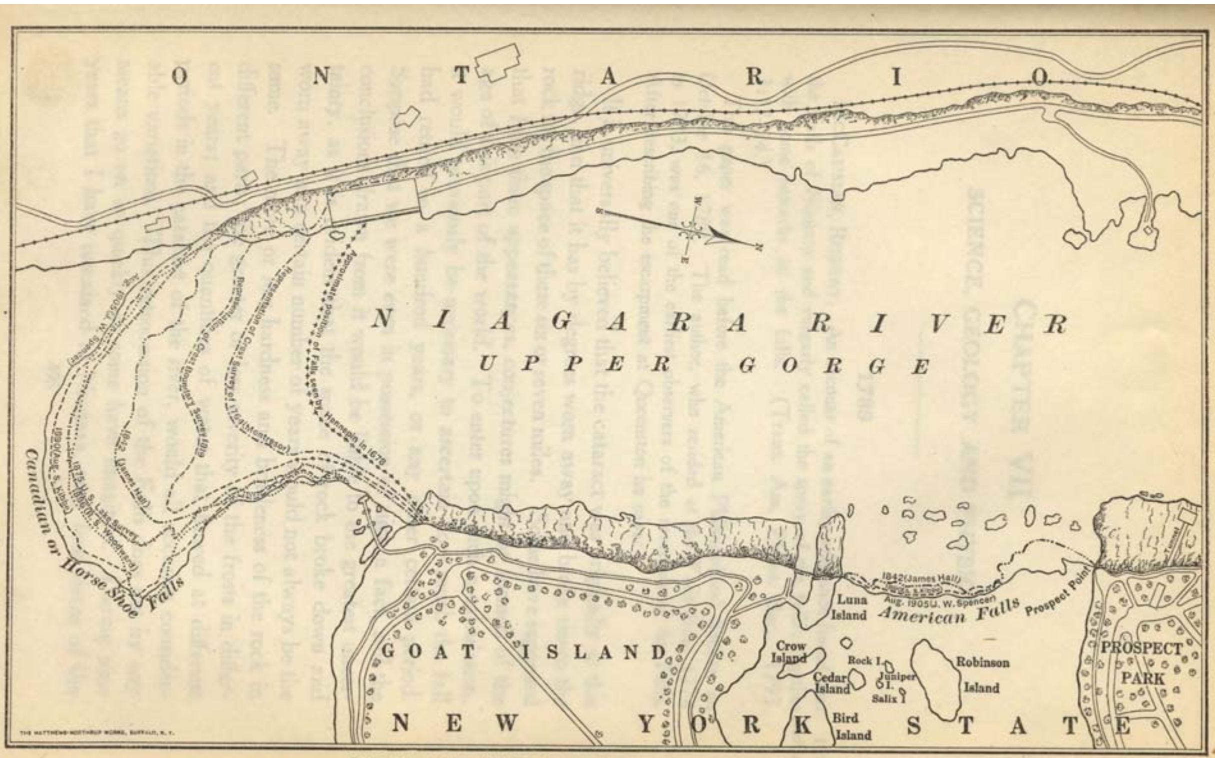


Figure 4: Hennepin's famous view of Niagara. Distant mountains may reflect the original European artist's prejudice that large lakes necessarily required the presence of large mountains; but at least on the New York side of Lake Erie the rising land towards Pennsylania is at least as prominent as the Niagara Escarpment – named at that time a "branch of the Alleghany Mountains" was from the Lake Ontario shoreline. A three-masted ship is however, well ahead of its time in 1678. The prominent spout of water on the right comes from behind what came to be known as Table Rock – a tourist point until it fell in the mid 1800s. The poresent Hotrel takes its name from the spot. In fact this marks a separate flow of water to that location up until about 1800. Its route is marked by the "meander" of Dufferin's Island, and a long lake that lay west of a remnant of the bed of Lake Tonawanda called Cedar Island on early maps. It is likely the dismembered remnant of the Chippewa Creek (Welland River) which became trapped behind a beach bar developed at the west end of Lake Tonawanda. It was dismembered as Lake Tonawanda drained and the river washed away many of the lake bottom sediments.

Figure 5: An extract from an imaginary panorama showing the industrial development at the river's edge in Niagara Falls, New York around 1900. There are feeder canals from the upper river to the water mills at the gorge's edge. The belt railway was a two track railway along the bottom of the gorge on the American side. It was closed in 1935 after severe rockfalls and the track has now vanished in several sections.

Because of lowered water level during power extraction upstream walls train water so the crest is always covered. The extraction has the effect of lowering the level of the Maid-of-the-Mist Pool by 10 or 15 feet (3 to 4 metres). In the later 1960s consideration was given to raising the water level to pre-extraction levels using a submerged weir at the entrance to the Whirlpool Rapids. At the same time the American channel was diverted with a coffer dam and repairs effected to the cliff face. In the end no change was made to the water level in the pool.

Niagara's rapid recession has long been noted. Figure 6 shows recession measured in the later nineteenth century – when there was concern rapid recession might overwhelm power intakes; and Figure 7 shows the original diagram by Gilbert upon which many waterfall "recession" diagrams in textbooks are based. Undercutting certainly takes place above the water level, but there is no evidence at Niagara – and little if any reported elsewhere, for undercutting in the plunge pool. In subsequent uses Gilbert omitted his original "theory" caveat.



MAP ILLUSTRATING RECESSION OF NIAGARA FALLS
Showing lines of brink of the falls at different dates

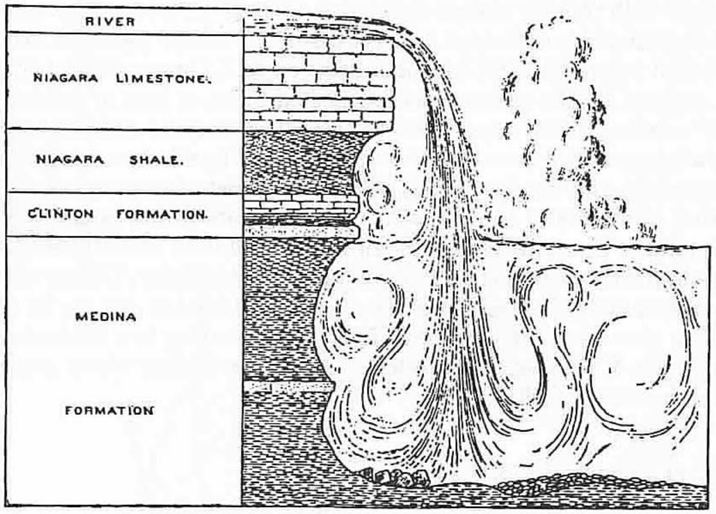
Figure 6: A map of some measured positions of the crestline marking the recession of Niagara Falls. The crestline position is probably only reliable during the 19th century from 1843 onwards (the Hall survey, Hall 1843). The Hennepin in 1768 is very approximate.

Modern ecological considerations

The remit of the Niagara Parks Commission - one hundred years ago – was primarily ecological – to restore Niagara to its pristine condition and to preserve its natural beauty. An act of 1885 required the Parks Commission to:

… preserving as far as possible what still remains of the natural and the original, and to endeavor to restore those portions of the ground on and near the bank of the river, within the limits surveyed, which haven been denuded of trees … to as near their natural condition as possible (Gzowski et al. 1886; de Gruchy et al. 2001).

A study of the ecology of the Maid-of-the-Mist landing site on the Canadian side (de Gruchy et al. 2001) set out to compare the Gorge side slope with a reference established from Niagara Escarpment sites elsewhere characterised by the authors (Larson & Spring et al. 1989). Three Niagara Falls sites, last disturbed at respectively 100, 30 and 4 years, showed significantly reduced in species richness, and it was concluded that current recovery is leading to a urban forest state, dominated by aliens, and that restoration to near-original conditions would active measures. A very complete ecological study of Goat Island with comprehensive historical analysis and species lists, can be found at a web site provided by Eckel (2002).



Gilbert's famous diagram of Niagara Falls (Gilbert, 1890a). It has been very widely disseminated and is still found in modern textbooks illustrating waterfall retreat in general, and Niagara in particular. The original caveat '... illustrating a theory of the process of erosion' was never subsequently used, even by Gilbert!

Gilbert, below, using his own diagram without caveat

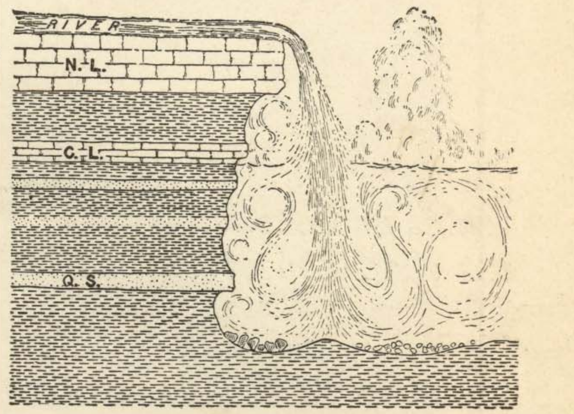


FIG. 10.—Profile and Section at Middle of Horseshoe Fall, showing Arrangement of Rocks and Probable Depth of Pool under Fall.

N.L., Niagara limestone; C.L., Clinton limestone; Q.S., quartzose sandstone. Scale, 300 feet = 1 inch.

Figure 7: Two illustrations of Gilbert's diagram of Niagara Falls, The upper one had a caveat noting it was a theory – a qualification that failed to follow the diagram thereafter, even when Gilbert used it (bottom diagram).

The total failure of their activity in the last hundred years with regard to this statement is quite clearly seen in front of you, and shows no sign of changing. A recent proposal was made to install a cableway along the Canadian shore, as yet another “attraction”. Already two sets of helicopters fly over the Falls, two sets of boats plough the pool, descents can be made to near the water level on both sides of the river, millions throng both sides of the Falls in a year, and endless retail outlets and parking lots cater to their numbers.

Niagara Falls Mist Plume (Overlook at Terrapin Point)

At this stop, we will look at the atmospheric mist plume generated by Niagara Falls (Fig. 8). Recently, the mist plume has attracted an unusual amount of attention because of the potential effects on the plume by building high-rise casino hotels in Niagara Falls, ONT (Galloway, 2004). The plume can be thought of as either one of the attractive aspects of the falls, or to most people, a nuisance that contributes to obscuring the view of the falls. It is thought that the high rises might be changing the flow of air around the Horseshoe Falls in such a way as to obscure the view of the falls by moving the average position of the mist plume towards the Canadian shore. The shoreward movement is hypothesized to be caused by flow separation over the high rises causing the formation of a recirculation zone (RWDI, 2004). The issue is important, as 14 million visitors come to the Canadian side every year for the express purpose of viewing the waterfalls (NPC, 2005).

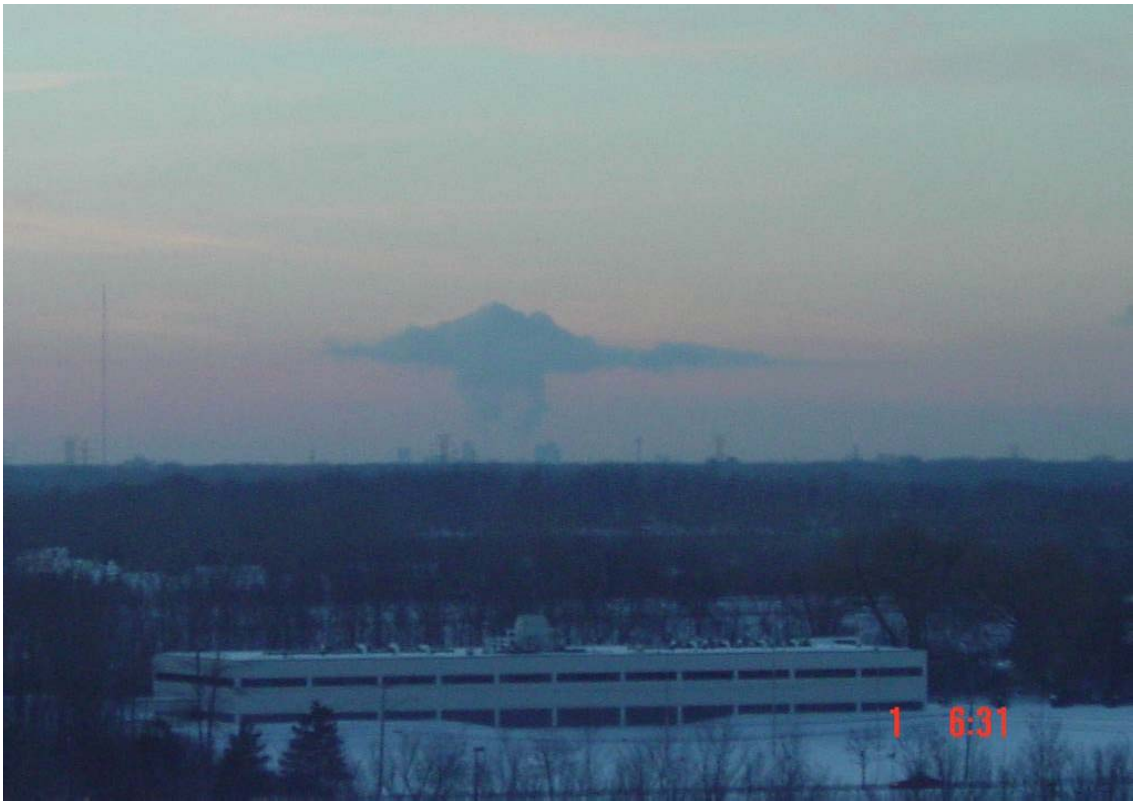


Figure 8: Photograph of the Niagara Falls atmospheric plume from the seventh floor of a building in Amherst, NY (distance approximately 20km).

Hydrodynamic and Aerodynamic Aspects of the Lower Niagara River (by Marcus Bursik)

The plume is formed by the impact of falling water on the plunge pool and rock wall surfaces, which generates a water aerosol jet (Fig. 9). The aerosol jet has been observed to be generated on other waterfalls above a certain discharge or fall height (Fig. 10). Under the proper fluvial and atmospheric conditions, the jet at the Horseshoe Falls evolves into a plume that can be lofted up to at least 1.1 km (Case, 2004).

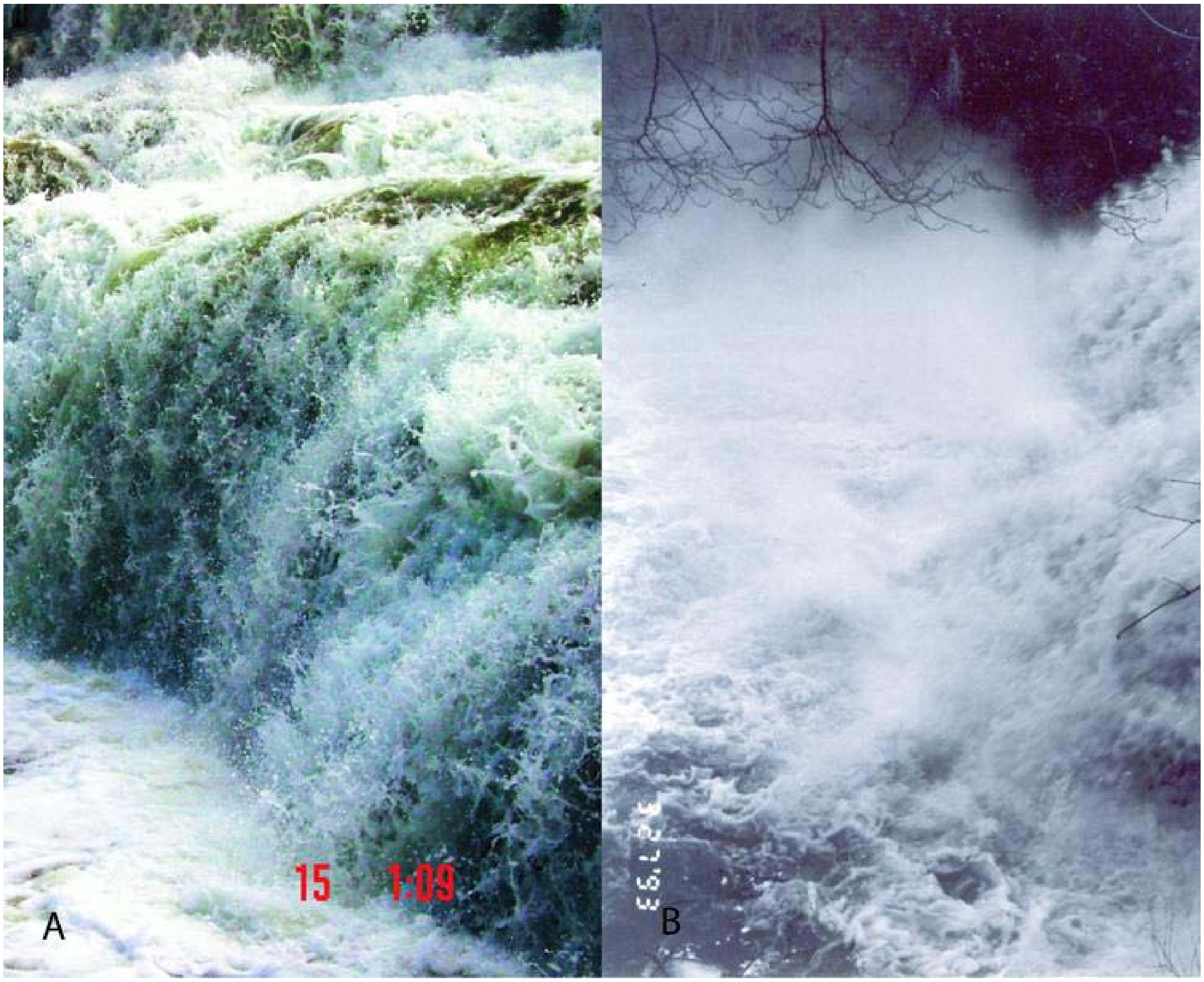


Figure 9: Two photographs of Glen Falls (Williamsville), NY, at lower (A) and higher (B) flow rates. At low flow rates, the impact of the falling water on the plunge pool surface is insufficiently powerful to aerosolize the rebounding particulates. At high flow rates, the pressure generated by the impact is sufficiently high to aerosolize the particulates.

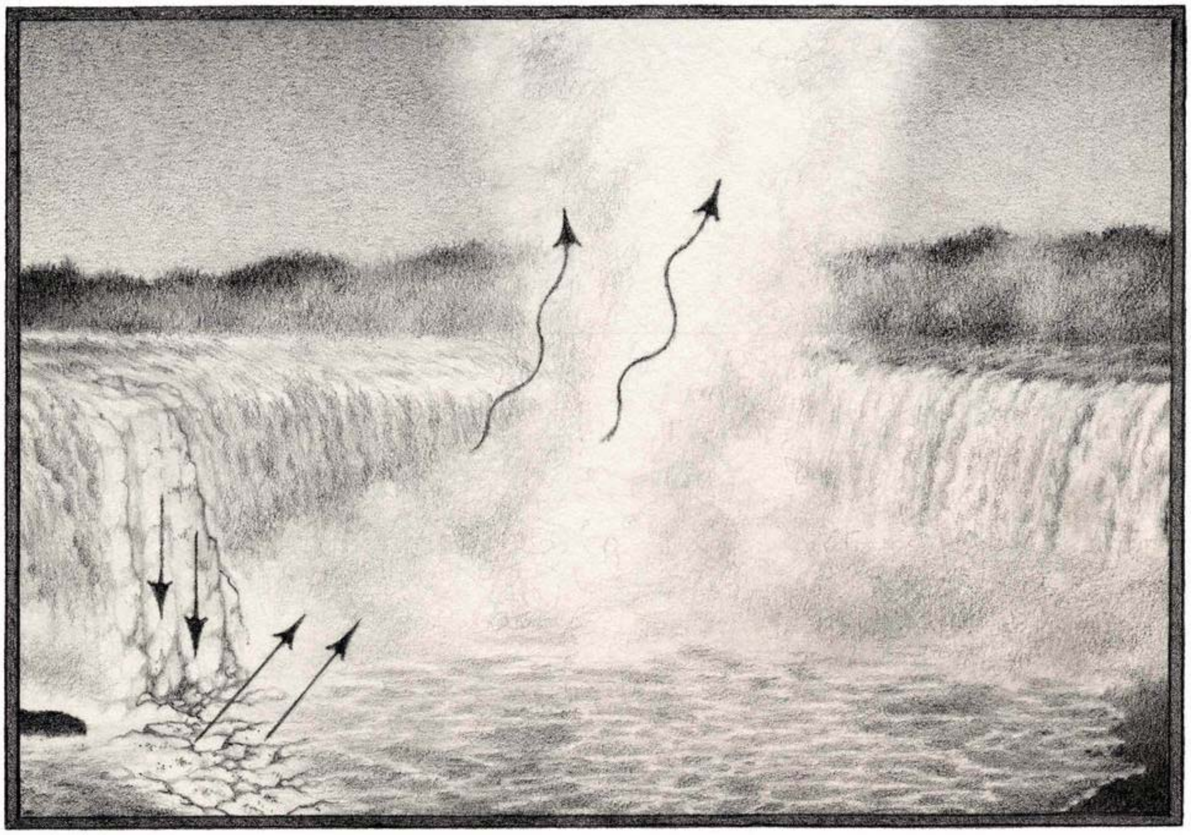


Figure 10: Schematic diagram showing the generation and lofting of the atmospheric waterfall plume at the Horseshoe. Drawn by R. Bursik

There are two lines of evidence that can be following in testing the flow separation hypothesis. In the first, the hypothesis is tested with straightforward studies of wind patterns in the vicinity of the Horseshoe. In the second, an alternative hypothesis is tested. In this test, it is assumed that enhanced obscuring of the waterfall is caused more by a volumetrically larger plume than by blowing of the plume shoreward. More specifically, we hypothesize that the mist plume, like other atmospheric plumes, is driven upwards by buoyancy. Furthermore, the buoyancy develops because the density of the misty air above the falls is less than the density of the ambient atmosphere. The condition can only occur when the temperature of the water in the Niagara River is sufficiently high that when the mist mixes with the ambient atmosphere, the expansion of the heated air is great enough to cause the bulk density of the mixture of water aerosol and air to be less than the ambient air density. If this hypothesis is true, then the plume should rise higher on days wherein the temperature difference between river and air is greater. To test this hypothesis, we undertook a number of measurements of plume height at times of different river and air temperature.

In the first test, we measured wind patterns in the vicinity of the Horseshoe (Hess, 2005). The hypothesis of flow separation predicts that flow vectors at upper river level should point back towards the high rises (to the west and southwest) when the wind is from the west to southwest. Data were collected under a variety of prevailing wind conditions, as indicated by mean windspeeds recorded at Niagara Falls, NY. Examples for three characteristic days are discussed here (Plate C). On 17 January 2005, the wind was from the west as measured by the weather station at Niagara Falls, NY. Ground level flow winds on both sides of the Horseshoe were also nearly from the west, indicating no flow separation, and certainly no flow towards the Canadian side. On both 24 June 2005 and 11 July 2005, winds were from the southwest, with a slightly higher mean wind speed on 24 June. On 24 June, ground level flow measured on the American side was from the south-southwest, while that on 11 July was from the east-southeast. These data indicate that in general, no argument can be made for the occurrence of flow separation. On no day of measurement with prevailing winds from the west to southwest was east to northeast flow observed near the Horseshoe. However, it is apparent that some flow diversion is taking place under certain conditions, but the origin of this diversion is as yet unknown.

To test the hypothesis that the mist plume is an example of a buoyant atmospheric plume, and that the degraded view of the falls results from a greater heat flux from the river water into the atmosphere, it was necessary to measure plume height on different days, river water temperature, ambient atmospheric temperature, and river discharge over the waterfalls (Case, 2004). Using the theory of Morton et al. (1956) for buoyant atmospheric plumes, we can then test whether the relationship among these variables follows one of the two equations:

$$\log(H_T) = \log C_1 + (1/4)\log(Q\Delta T / T_a)g)$$

for a plume, or

$$\log(H_T) = \log C_2 + (1/4)\log(V(\Delta T / T_a)g)$$

for a discrete puff. In these equations, H_T is plume height, C_1 and C_2 are constants dependent on ambient atmospheric stratification, heat capacities and a constant of proportionality discussed below, Q is river discharge, V is puff volume, ΔT is temperature difference between river water and air, T_a is air temperature and g is gravitational acceleration.

River temperature was estimated to be the same as that recorded for Lake Erie, while air temperature at Niagara Falls was estimated from the temperature shown at the weatherunderground.com weather web site. The height of environmental plumes is not only strongly dependent on temperature difference, but also on flow rate into the plume. Because this quantity is difficult if not impossible to measure for the Niagara Falls atmospheric plume, we hypothesized that the flow rate might be proportional to the river discharge (Fig. 11). That is, for a higher discharge over the falls, and a constant fraction aerosolized, there will be a higher flow rate of aerosol into the plume. The flow rate over the falls (both Horseshoe and American) was estimated from the gauge data recorded at Ashland Avenue. This gauge is downstream of the falls, and probably provides the best estimate of the discharge going over the falls. An extended form of the rating curve of McMullin (1973) was used to map the gauge elevation values to discharges. Plume height was estimated by photographing or videotaping the plume while at the same time ensuring that the Skylon Tower was in each frame. Plume height was then scaled from the apparent height of the Skylon Tower. One feature that videotaping allowed us to measure was the occasional puffiness or transient behaviour of the plume (Fig. 12). Puffiness seemed more pronounced at lower discharge.

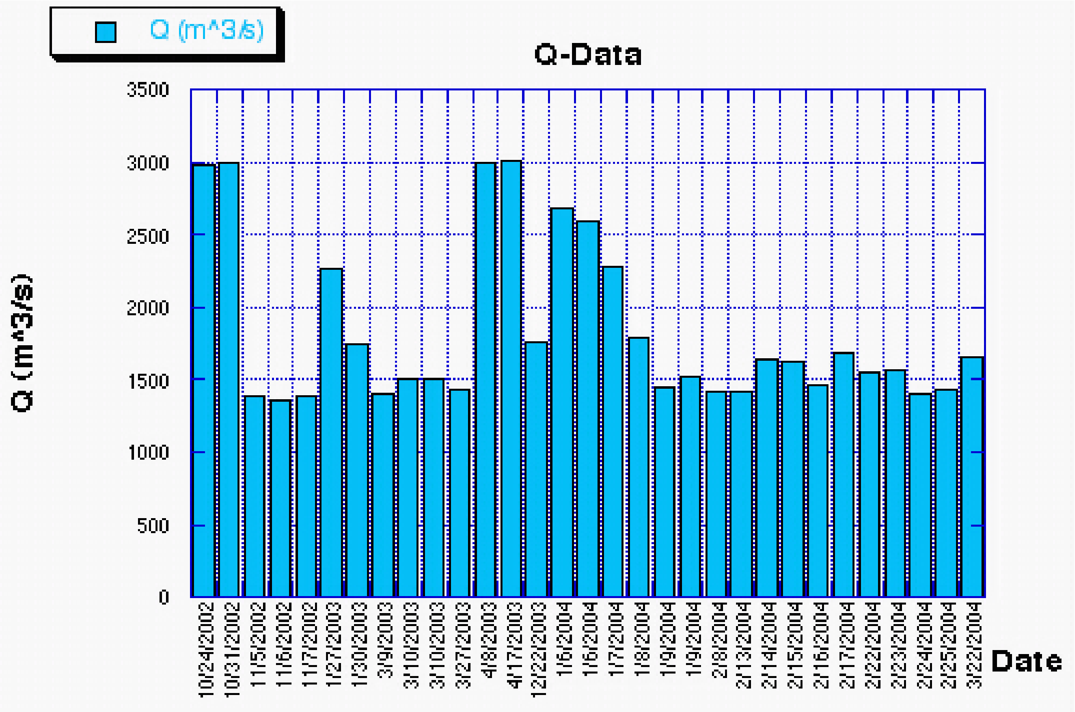


Figure 11: Flow rate of the Niagara River at the Ashland Avenue, Niagara Falls, station at the times that plume height data were gathered. We hypothesize that the flux of aerosol into the atmospheric plume is proportional to the flow rate of the river over the falls.

Using the data on air temperature, water temperature and discharge, and assuming a standard atmospheric stratification, we investigated the relationship between plume height and buoyancy flux (Fig. 7). For a steady plume, the model suggests that the plume or puff rise height should scale to the 1/4 power of discharge or puff volume. The results are consistent with the working hypothesis, although noisy. Linear regression yields a curve closer to the 1/3 to 1/2 power linking buoyancy flux (or buoyant volume) and plume height. Scatter in the data is reduced for times during which the wind was low (for example, below 25 kph), and we suspect it would also be reduced were we to have estimates of the atmospheric stratification parameter (rather than using a standard value). The results of these studies suggest that flow separation does not occur over the high rises, and that mist plume volume (hence potential to obscure waterfall view) is a product of ambient water and atmospheric conditions, irrespective of cultural features.

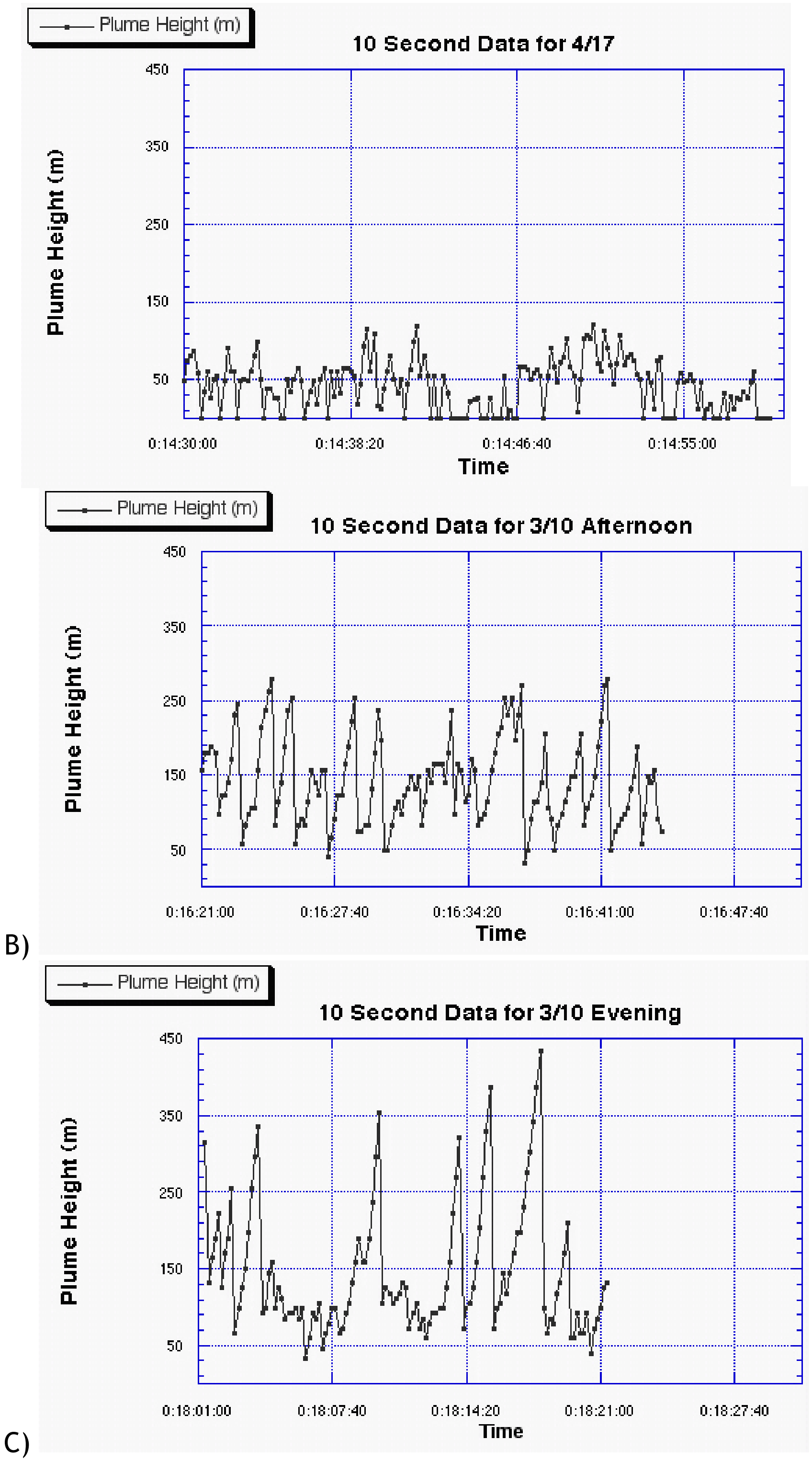


Figure 12: Measurements of plume height at three different times on a 10 s interval. DT in part A was lower than that in parts B and C. C was measured later in the same day as B, when wind and atmospheric stratification conditions may have changed.

Stop 2: Whirlpool State Park

A century ago several sites downstream of the Falls, and at the upper river level upstream of former positions of the Falls), where recorded as fossiliferous (Kindle & Taylor 1913) . However at this time the only site known to be exposed is Whirlpool State Park (Plate B). Shell rich exposures are visible just below the railings overlooking the gorge. Lyell and Hall first noted fossils here in the 1840s, Calkin & Brett (1978) were the first the dated them (between 9 Kyr and 10 Kyr BP). It is worth realising that when the shells were deposited the waterfall was at least a mile downstream and the river from the Whirlpool site to the waterfall was flowing over solid rock. However, in the region of the Whirlpool and upstream for over a kilometre, the upper river was flowing over soft sediments (silts and diamict) comprising the infill to the buried St Davids Gorge. It is highly likely that the river bed contained deeply scoured pools which formed an ideal environment for molluscs. Abundant large molluscs are preserved in the gravels at Niagara Glen as well as in the Whirlpool State Park gravels. The site is in a point bar situation as the upper river made a 90 degree turn, and rafting by winter ice may have ridden deposits even higher (in the historic period winter ice has reached 50 feet (15 m) above normal water levels.

Whirlpool Jet and Whirlpool Reversal (by Marcus Bursik)

At this site, we will discuss the Whirlpool entrance jet and the Whirlpool Reversal phenomenon in the light of the theory of fluvial jets entering shallow basins. The Whirlpool Rapids is the most turbulent reach downstream from Niagara Falls. The rapids can be divided into three major subreaches: the Upper Whirlpool Rapids, a highly turbulent and aerated reach, the Eddy Basin, a relatively wide, deep and calm reach, and the Lower Whirlpool Rapids (LWR), which ends in a set of large, breaking, standing waves at the entrance to the Whirlpool. The gorge in this reach is particularly narrow and steep. The canyon walls are 350 m apart instead of more typical distances of 500 m elsewhere. Our best measurements and observations of flow were made on April 11, 1998, when the discharge through the rapids was 2833 m^3/s. The depth of the river is 10 to 20 m (AFIB, 1974), and water speeds were measured to reach as high as 16 ± 4 m/s (35 km/h) in the slick tongue leading into the standing waves, on a mean gradient of 0.01 (about 16 m in 1.6 km) (AFIB, 1974).

The river surface displays a smooth but rapid drop of about 3 m in level at the entrance to the Whirlpool. The drop is followed by a group of stationary waves with crests that trend obliquely to the channel walls and become successively lower in amplitude downstream. The first and largest wave is a breaking wave about 5 m high. The location of the waves, their amplitude, and general characteristics remain fairly constant over any period of observation.

We surveyed the active channel through the Lower Whirlpool Rapids and found the width to be 100 m. We assume a rectangular channel cross-section, which is a reasonable simplification given the nearly vertical sand and siltstone confining walls. Observations of the bed where it is visible, as well as the river surface level are consistent with a steep increase in the bed gradient as the river enters the Whirlpool, perhaps even a steplike drop. The result is that the flow accelerates as the Whirlpool is entered, and a high, normal shock is formed. In planform, the river geometry is diverging as the Whirlpool is entered, and the normal shock that stands midriver joins the shoreline via two oblique arms that point upstream. Because the diverging geometry cannot result in oblique shock formation, these oblique waves must be caused by the bed geometry. The implication therefore, is that the steep declivity in the channel bed includes a promontory midstream, i.e., the lip of the bed elevation drop is further downstream in the middle of the river.

The normal shock can be analyzed using one-dimensional shock theory. Over a short distance, the flow can be assumed inviscid, with negligible lateral accelerations. The Euler equation is valid for any streamtube under these conditions and is derived from the conservation of momentum:

$$u^2/2g + h + z_0 = H$$

where u , h and z_0 are local values for flow speed, depth and bed elevation respectively, $u^2/2g$ is the velocity head, $h + z_0$ is the piezometric head and H represents total head. Since $H - z_0$ equals the specific energy density (E), substitution into the above equation with some algebraic manipulation yields:

$$Eh^2 - h^3 = q^2/2g$$

Where q is the unit discharge (discharge per unit flow width). This equation describes the possible energy densities occurring in a flow, and for a constant discharge will yield E for given flow depths.

The Froude number (Fr) is the ratio of kinetic to potential energies. A Froude number greater than one indicates that kinetic energy is greater than potential energy; the flow will therefore be supercritical. Conversely, a Froude number less than one is indicative of slow, deep subcritical flow. The subcritical and supercritical regimes correspond to two arms of a hyperbolic curve characteristic of the $E - h$ relation. The Froude number is calculated as:

$$Fr = u^2/gh$$

We calculated flow conditions at three channel cross sections. For the first channel section we used the width, depth and discharge measurements to determine an average water velocity, $u_1 = 11.4$ m/s. This value was input into the Fr and $E - h$ relations to yield $E_1 = 16.6$ m and $Fr_1 = 1.15$. The Froude number here indicates supercritical flow.

A 3 m drop in water level was observed during field investigations. The only explanation consistent with a sudden water surface drop in the supercritical flow regime is a down drop in the channel floor. This down drop causes the flow to gain kinetic energy; to conserve total energy the flow must decrease in height thereby lowering the potential energy. The increase in specific energy is accounted for by a drop in the channel floor expressed as:

$$E_2 = E_1 + \Delta z_0$$

The observed surface downdrop is therefore due to the sum of the decrease in flow height and the downdrop of the channel floor. Inverse calculation, using the observed surface downdrop and the $E - h$ relation, yielded a flow thinning of 1.7 m (to 8.3 m depth) and a down drop of 1.4 m. This equals the total observed three-meter downdrop. The decreased water depth causes an increase in velocity and hence Froude number, calculated respectively at 13.8 m/s and 1.5; again flow is supercritical.

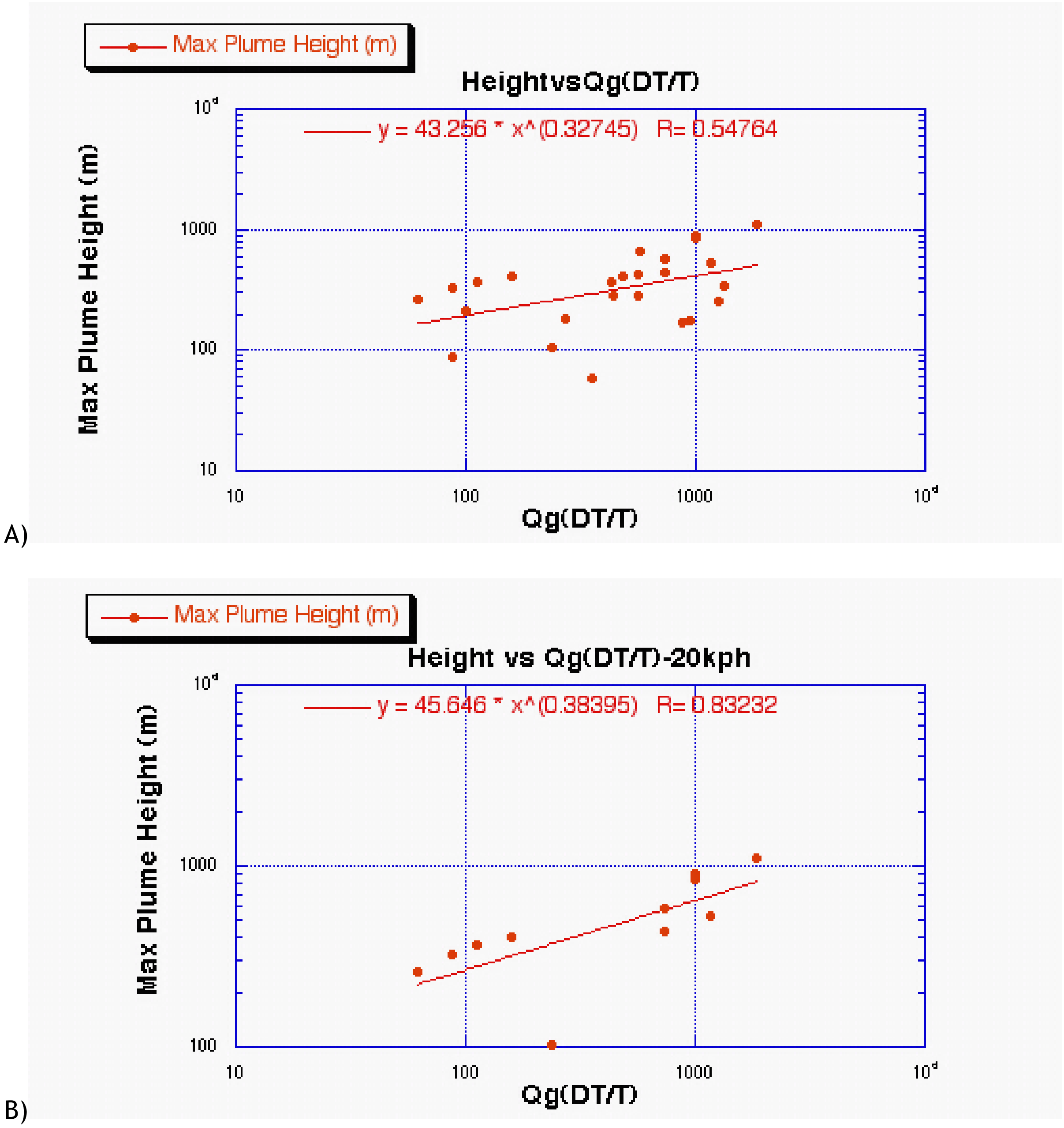


Figure 13: A) All data for plume height as a function of buoyancy flux, $Qg(T_m - T_a)/T_a$, where Q is Ashland Ave. discharge, g is gravitational acceleration, T_m is mist temperature (river temperature) and T_a is air temperature. Bouyancy flux is related to heat flux at the source. B) For times during which the wind speed was less than 20 kph. This decreases the scatter.

A group of stationary waves occurs just beyond the water surface drop, the largest of which was estimated in the field to be approximately 5 m. The presence of whitewater on wave crests indicates the occurrence of aerated flow due to high turbulence generated by the breaking wave. Turbulence implies that mechanical energy is not conserved and total head is not constant. We also do not believe that the jump in the water surface is caused by a step-up in the channel floor as we know from bathymetric surveying that the river bottom descends to the center of the Whirlpool. We therefore hypothesize that the observation is consistent with rapidly varied flow. Hence the breaking wave is a hydraulic jump, across which the ratio between the flow depths is given by:

$$h_3 / h_2 = [(1 + 8Fr_2^2)^{\frac{1}{2}} - 1] / 2$$

Using the results from our calculations at the second cross section, and solving for h_3 yields the water depth in this cross section to be 13.9 m. This is 5.6 m above the water surface at the second cross section, and consistent with field observations. A lower velocity (u_3) of 8.2 m/s for the given depth is consistent with subcritical flow, as given by $Fr_3 = 0.70$. Thus, there is a flow transition (shock) at this river section, from supercritical to subcritical. Laboratory experiments on flow transitions have shown that characteristic waveforms are a function of the Froude number. Experiments in the $1 < Fr < 1.7$ range show the dominance of an 'undular jump' characterized by a large standing primary wave, with a succession of ever diminishing waves downstream, consistent with observations in the LWR.

The Whirlpool jet represents the transition from typical open-channel flow in the LWR to the rotating flow pattern of the Whirlpool. MacMullin (1973) documented a reversal from normal counterclockwise to clockwise flow within the Whirlpool that occurred during times of diversion and flow < 62 000 cfs (< 1756 cu m/s). He inferred that the reversal was the result of the shape of the rocky weir guiding the influent jet. Two sets of laboratory experiments and numerical analysis were performed to understand the hydrodynamics associated with a jet entering a shallow, restricted basin, as is the Whirlpool. The working hypothesis for this research was that the jet behaviour results from hydrodynamics, specifically that the direction that the jet takes into the Whirlpool results from the interaction between the jet and the walls of the Whirlpool to induce a Coanda effect (drawing of the jet towards the wall) under certain flow conditions (Fig. 14).

The Coanda effect occurs when a jet enters a basin sufficiently restricted that the entrainment demands of the jet cannot be met (Rajaratnam and Subramanya, 1968). In such a case, a low pressure area forms on the side of the jet near the closest wall, drawing the jet towards the wall. Thus, we might expect that for river discharges below a certain level, entrainment demands can be met and there is no Coanda effect and jet-wall impingement. However, as discharge increases, it may be that the increased entrainment demands are not met, and the Coanda effect is induced.

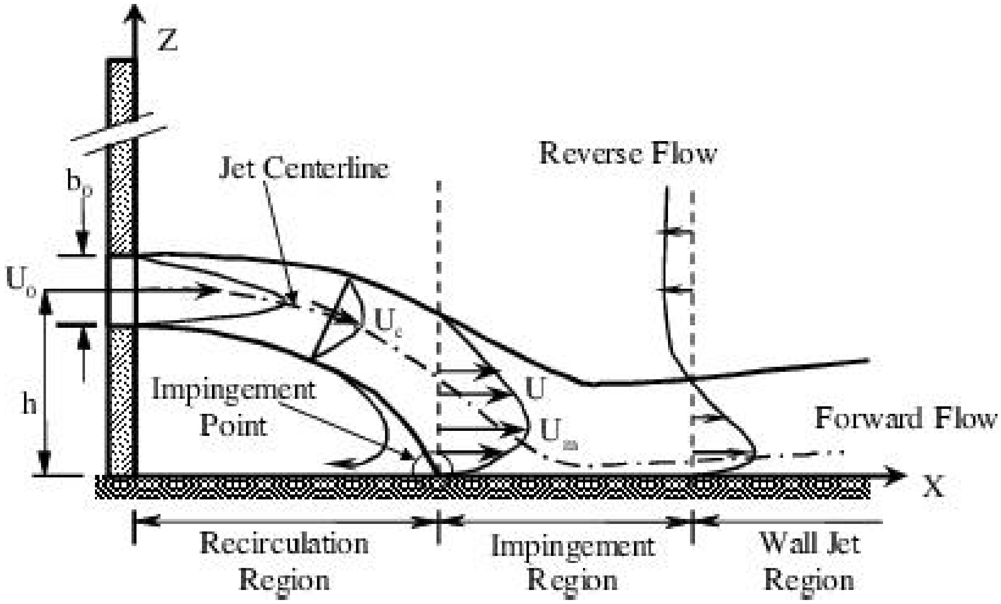


Figure 14: Schematic diagram of a jet entering a shallow basin, such as the Whirlpool, and being subjected to the Coanda effect. Note the recirculation zone toward the wall from the jet as it enters the basin (from Ku, 2000).

The dynamics of a clear-water jet discharge across a submerged knickpoint similar to that found in the Whirlpool was studied in a set of laboratory experiments to determine the dynamic and geometric conditions under which impingement occurs (Balasubramanian, 2001). This was done by initiating a surface discharge, either buoyant or non-buoyant, into a shallow receiving basin. Measurements of bottom pressure were analyzed to determine conditions of recirculation and bottom attachment, consistent with the occurrence of the Coanda effect (Fig. 15). We found that the Coanda effect and bottom attachment result in a peak in basal pressure and large-scale eddy formation even when the discharge is buoyant, for sufficiently high Reynolds number (Fig. 16). However, at inlet Reynolds number below about $\mathrm{Re} = 3000$, there is no low-pressure area and no attachment occurs. Although the scaling between the two-dimensional laboratory experiments and the three-dimensional flow in the Whirlpool has not been worked out, this result suggests that below a certain flow Reynolds number, the Whirlpool jet will not attach, and therefore, flow circulation sense will change. This is consistent with the observation that circulation direction change is induced by a drop in discharge (flow Reynolds number). At lower flow rate and Reynolds number, jet reattachment may not occur, hence flow is not drawn to the bank of the Whirlpool and flow is clockwise. At higher flow rate, the Whirlpool jet attaches to the the American bank, and flow circulation direction is counterclockwise.

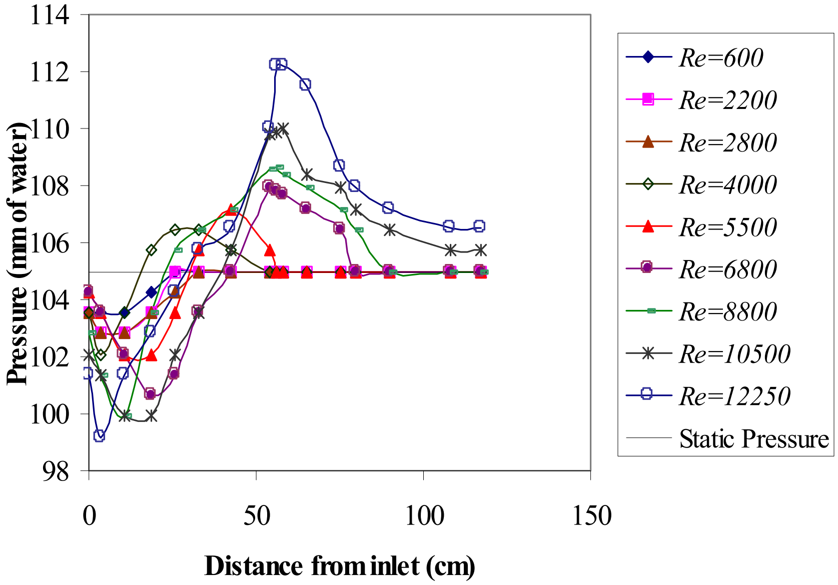


Figure 15: Bottom pressure measurements for a number of flow conditions. Discharge and ambient density were varied. The influent was always freshwater at the same temperature as the ambient. Upper panel, at lower Reynolds number, there is no bottom attachment as indicated by the lack of a maximum in basal pressure. Lower panel, jet impingement is indicated at higher Reynolds number by a peak in basal pressure.

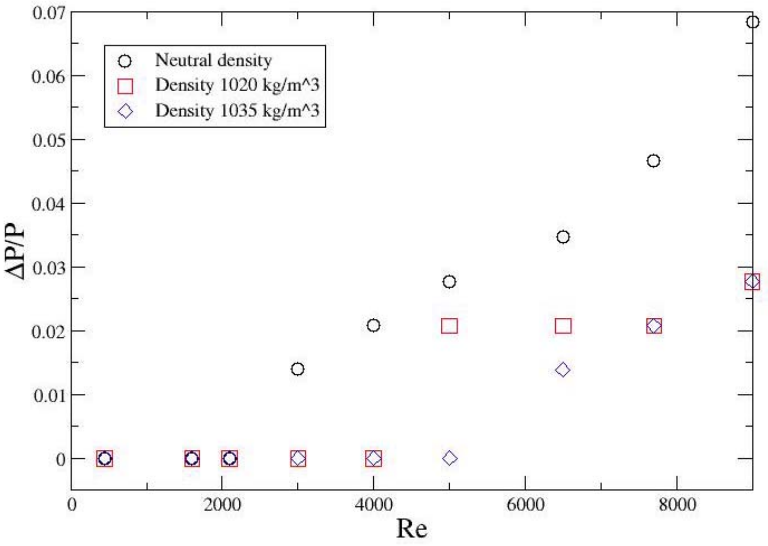


Figure 16: Maximum bottom pressure deviation from hydrostatic at the impingement point as a function of inlet Reynolds number. As expected, the pressure anomaly increases with higher Reynolds number (and lower density contrast).

Stop 3: Niagara Glen

Downstream from the waterfall we can glimpse Niagara Glen – sticking out into the otherwise clean U-shape of the gorge like a sore thumb. The Glen marks where the river was stalled for about 5000 years between 10,500 and 5,500 Yr BP – ther Erie “Phase” (Tinkler et al. 1994). At this time upper Great lakes waters drained directly to the Mattawa and Ottawa Rivers past North Bay, and Niagara Discharge was less than 10% of the present value. In consequence there was a much smaller river, although even so the discharge was steady – being buffered by Lake Erie.

Recession was probably the order of only 10 cm a year (Tinkler et al 1994), and the plunging jet could not penetrate the Whirlpool Sandstone which acts as the floor for the plunge pools at the period. The steady flow of a lake-buffered discharge is not easily modulated by transient flood flows and as with the present lakes secular variation in lake level would reflect seasonal and longer hydrologic trends averaged across the basin. However, wind-sets on Lake Erie can mimic floods. Wind blowing strongly along the axis of Lake Erie (SW-NE) as low pressure systems pass through, can raise water levels at Buffalo by up to 2.5 meters in extreme cases, and for a few hours. The response is substantially more water flowing into the Niagara River.

At present average discharge and lake levels this is sufficient to increase discharge in the river by 50 to 75% of the base value for a few hours. In the case of the discharge in the Erie “Phase” when the waterfall was at Niagara Glen the same magnitude of water level rise on lake Erie would enhance the flow to close to modern average discharge – i.e. ten fold increase in flow. This would have had a dramatic effect on the waterfall, enabling debris and sediment to be mobilised and the morphology of the Falls crest and plunge pools to be “cleaned”. The lack of persistence though would mean that the lower steady discharge prevailed as the primary driving force in the morphogenesis.

The modern River bypasses the Glen on the river right (east) side to form the Devil’s Holes rapids, through a narrower gorge, presumably ripped out when 100% flow was re-established once isostatic rebound decanted the upper Great Lakes over the Detroit sill and back into Lake Erie.

The Whirlpool was not created until about 4500 years ago when the water fall retreating from Niagara Glen through solid rock, broke through the rock wall and exposed the buried gorge. No doubt the soft sediment in fill was rapidly excavated, as far as the buried gorge went upstream, and gorge cutting was re-established just south of the head of the Whirlpool Rapids.

Robert Moses and Adam Beck Power Stations

Water drawn from the upper river, above the Falls, is fed through canals to the power stations. On the American side water is stopped in an excavated reservoir, on the Canadian side in a reservoir ponded above the plateau level. There are proposals to build an additional feeder canal on the Canadian side which would enable more efficient use of the Canadian water allocation, but would not involve additional withdrawals.

This section of the gorge is called the Old Narrow Gorge in the older literature (Kindle and Taylor (1913), although the cross-section is not greatly different from that of the Upper Great

Gorge. Allowing for 12,000 years of slope erosion, it may perhaps have been narrower originally, but insufficiently smaller to suggest the discharge at the time was materially less than at present. Tinkler et al. (1994), using data from Teller (1990), show that original discharge was similar to the modern one – although the sources for the water was somewhat different.

A recent announcement by the Ontario Provincial Government states that a third tunnel will be build to make water utilisation at the Adam beck 14% more efficient. No additional water can be taken under existing agreements. Exploration for this tunnel in the late 1980s and early 90s produced a further radiocarbon age on organic remains in the buried gorge fill (Abidi et al 1992).

Stop 4: Hidden in full view – the Lower River: the "Unknown" Niagara Gorge (with Marianne Ferencevic)

The Niagara Gorge between the Falls and Queenston/Lewiston has been an object of fascination – not least geologically – for several centuries (Tinkler 1987, 1994). By the 1840s, the existence was established of a buried gorge leading from the right-angle bend at the Whirlpool to a subdued break in the rock wall of the Escarpment at St Davids (Lyell 1845, Hall 1843, Tinkler 1994). In this century the buried gorge has been followed out across the Iroquois lake bed to the north (Hobson & Terasmae 1968, Karrow & Terasmae 1970). However, despite more than two centuries of geological description there has been astonishingly little description of the substantial and very visible gorge below the Escarpment between Queenston and Niagara-on-the-Lake.

We can find no more than a handful of publications and several sentences that mention the gorge. It is in full view as the lower Niagara River; about 500 m wide, typically 10 to 15 m deep, with channel banks rising up 20 above the water level on both sides. Thus, over the 12 km length of the gorge it has an approximate volume of 96 x 106 m3. This compares to an estimated volume of 317.4 x 106 m3 for the usually recognized gorge – of which however 64.8 4 x 106 m3 is normally interpreted as belonging to the "buried" St Davids pre-Late Wisconsinan gorge active prior to 24,000 BP. Thus the unknown gorge has approximately 40 percent of the volume of the "normal' gorge, and has been eroded within the same time period. This calls for some discussion. No volume estimate has been made for the section of the buried gorge extending from St Davids northwards to Lake Ontario – but general indications from the map in Hobson & Terasmae (1968) suggest it would have a similar volume to 'unknown' gorge.

Once the ice from of the Laurentian Ice Sheet had withdrawn across the present Lake Ontario basin, water was ponded against the Niagara Escarpment to form proglacial Lake Iroquois (initiated circa 12,600 BP), whose outlet was south-eastwards past Rome and Utica into the Mohawk and then to the Hudson valley. There may have been very temporary, higher level lake phases preceding Lake Iroquois, but their traces are scattered and indistinct. Strong isostatic rebound across the Ontario basin (Clark 1994 et al.) meant that Lake Iroquois's water level was always rising on the southern shore, and during its existence for less than a millenium it cut a cliff line back across the diamict drape on the southern flank of the Ontario basin. In most places the shoreline that remained when the lake drained suddenly (at about

11,800 BP) is several kilometres north of the Niagara Escarpment, but at the Niagara River the shoreline was very close to the bedrock, cutting a steep cliff into diamict preserved west of Queenston immediately north of Route 81.

The present 'unknown' gorge will have been largely excavated as the level of Lake Iroquois dropped when the Laurentian Ice Sheet receded far enough to the north west to open up the isostatically depressed St Lawrence valley. The lowered water level would expose the lake bed of former Lake Iroquois, and the lower Niagara River would extend over it developing a channel.

The Queenston shale is easily incised under wetting and drying conditions and numerous other deep gorges partly cut in Queenston Shale are known along the shores of Lake Ontario. Isostatic tilting affecting the Ontario basis has raised the outlet end at Kingston so that lake waters have ponded against the southern shore flooding into incised valleys along the southern shore and backing up the Niagara River to make its present form.

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Plate A: The full (and extremely detailed) key is not provided in this excerpt of the detailed geological map of Niagara in Kindle and Taylor's (1913) "Niagara Folio." It identifies the Niagara Fall's moraine which acted as the eastern shoreline of lake Tonawanda. Notice the Lake boundary through Niagara Falls, New York,, and the depths shown in the Maid-of-the-Mist Pool.

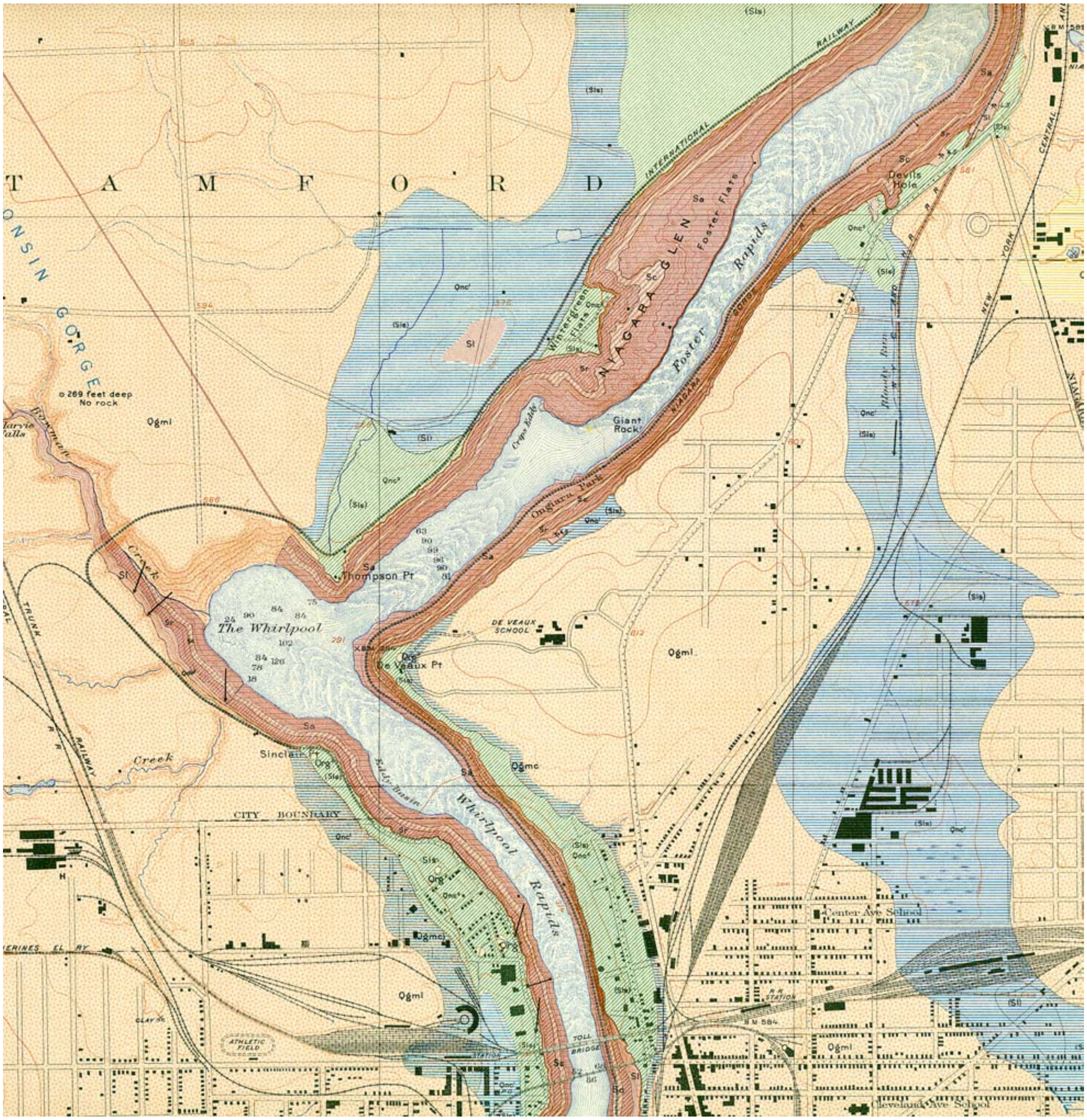


Plate B: An extract from the same Kindle and Taylor (1913) map for the Whirlpool section of the river. The buried St David's gorge goes off to the North West and is marked "Wisconsinan Gorge." The Niagara Falls spillway – which never developed as a gorge, is seen on the right (east) side of the maps.

A)

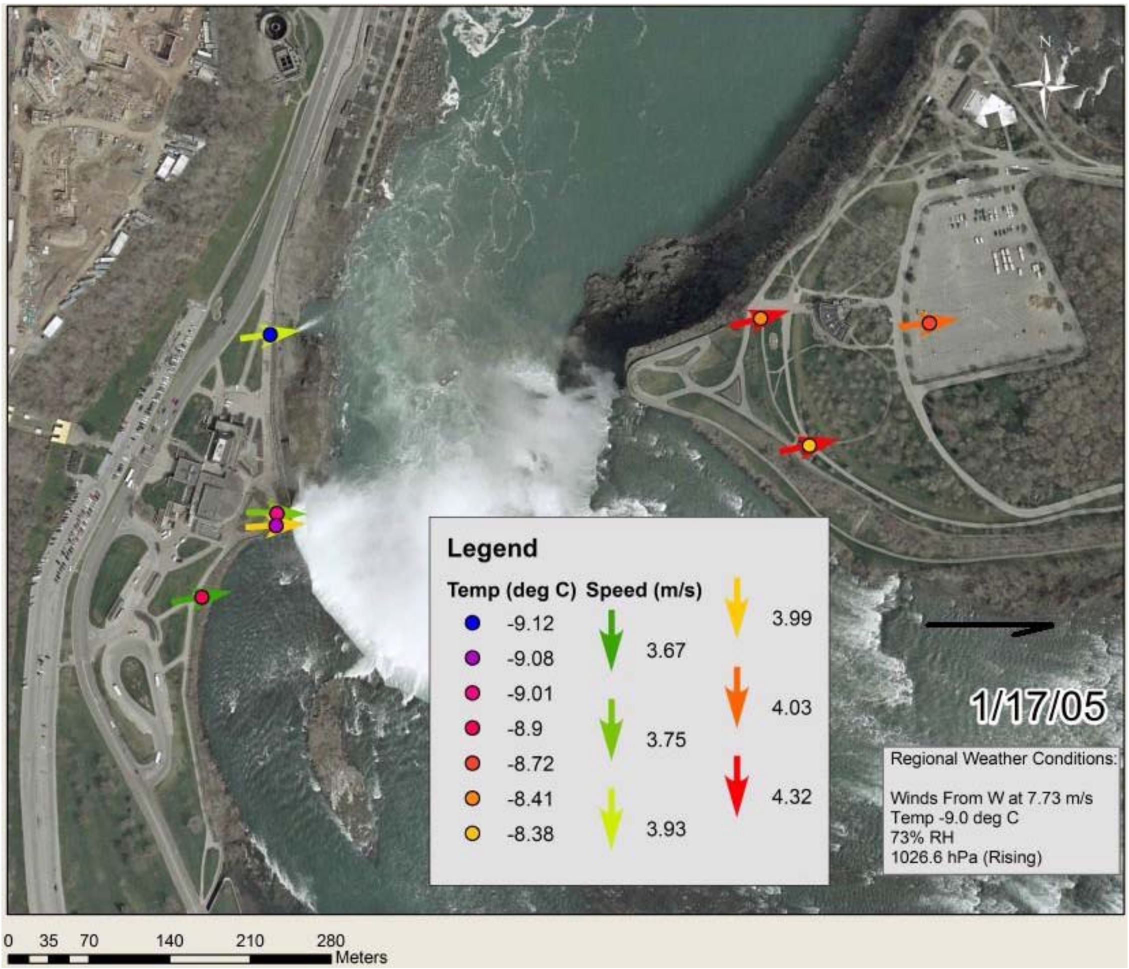
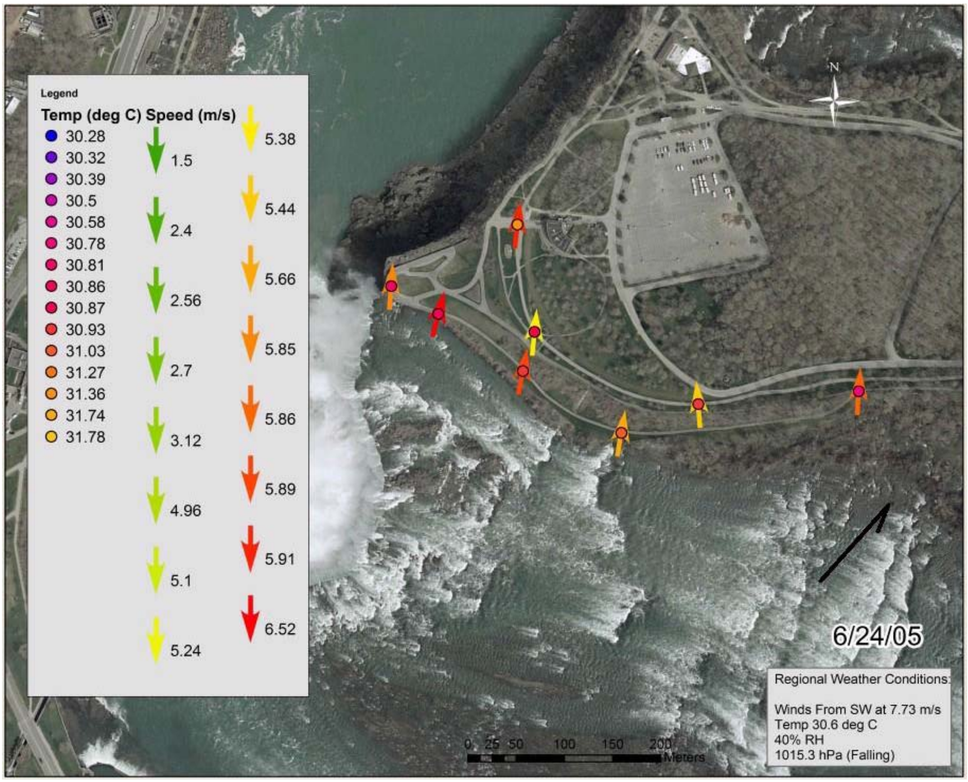
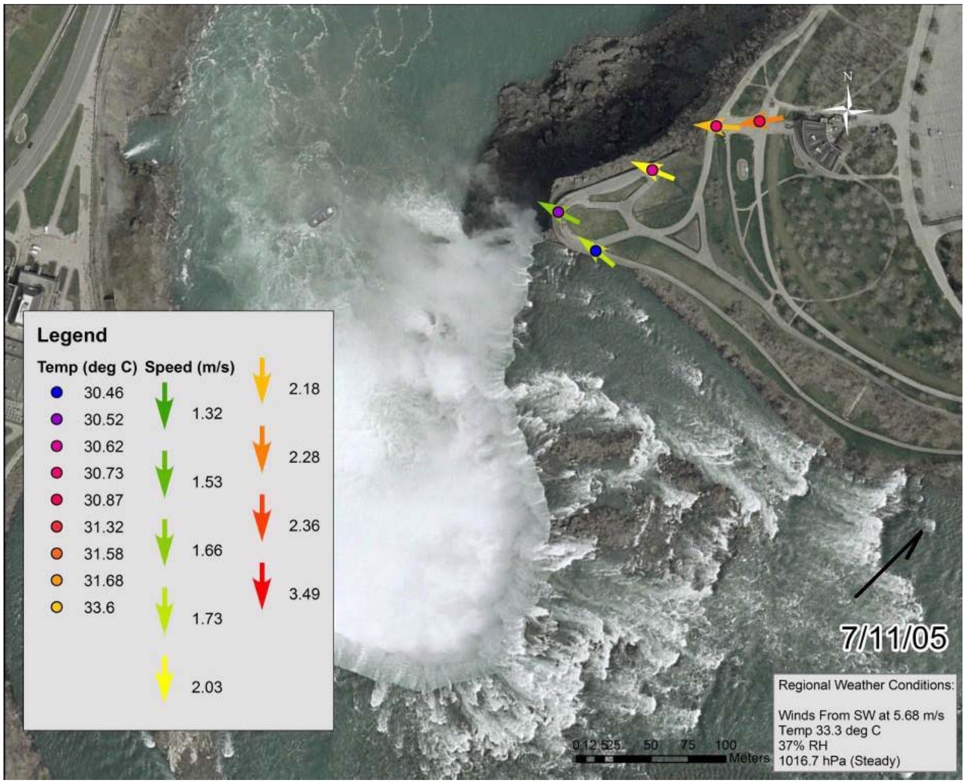


Plate C: Local weather measurements in the vicinity of the Horseshoe on days when the wind was from the W to SW. Arrows point in the direction towards which the wind was blowing at three dates: A) 1/17/05, B) 6/24/05, and C) 7/11/05. Note that the measurements are on the same aerial photo.

B)


Legend
Temp (deg C)
30.28
30.32
30.39
30.5
30.58
30.78
30.81
30.86
30.87
30.93
31.03
31.27
31.36
31.74
31.78
Speed (m/s)
1.5
2.4
2.56
2.7
3.12
4.96
5.1
5.24
5.38
5.44
5.66
5.85
5.86
5.89
5.91
6.52
N
6/24/05
Regional Weather Conditions:
Winds From SW at 7.73 m/s
Temp 30.6 deg C
40% RH
1015.3 hPa (Falling)
0 25 50 100 150 200
Meters

C)


Legend
Temp (deg C)
30.46
30.52
30.62
30.73
30.87
31.32
31.58
31.68
33.6
Speed (m/s)
1.32
1.53
1.66
1.73
2.03
2.18
2.28
2.36
3.49
N
7/11/05
Regional Weather Conditions:
Winds From SW at 5.68 m/s
Temp 33.3 deg C
37% RH
1016.7 hPa (Steady)
0 12.5 25 50 75 100
Meters

D

Notes

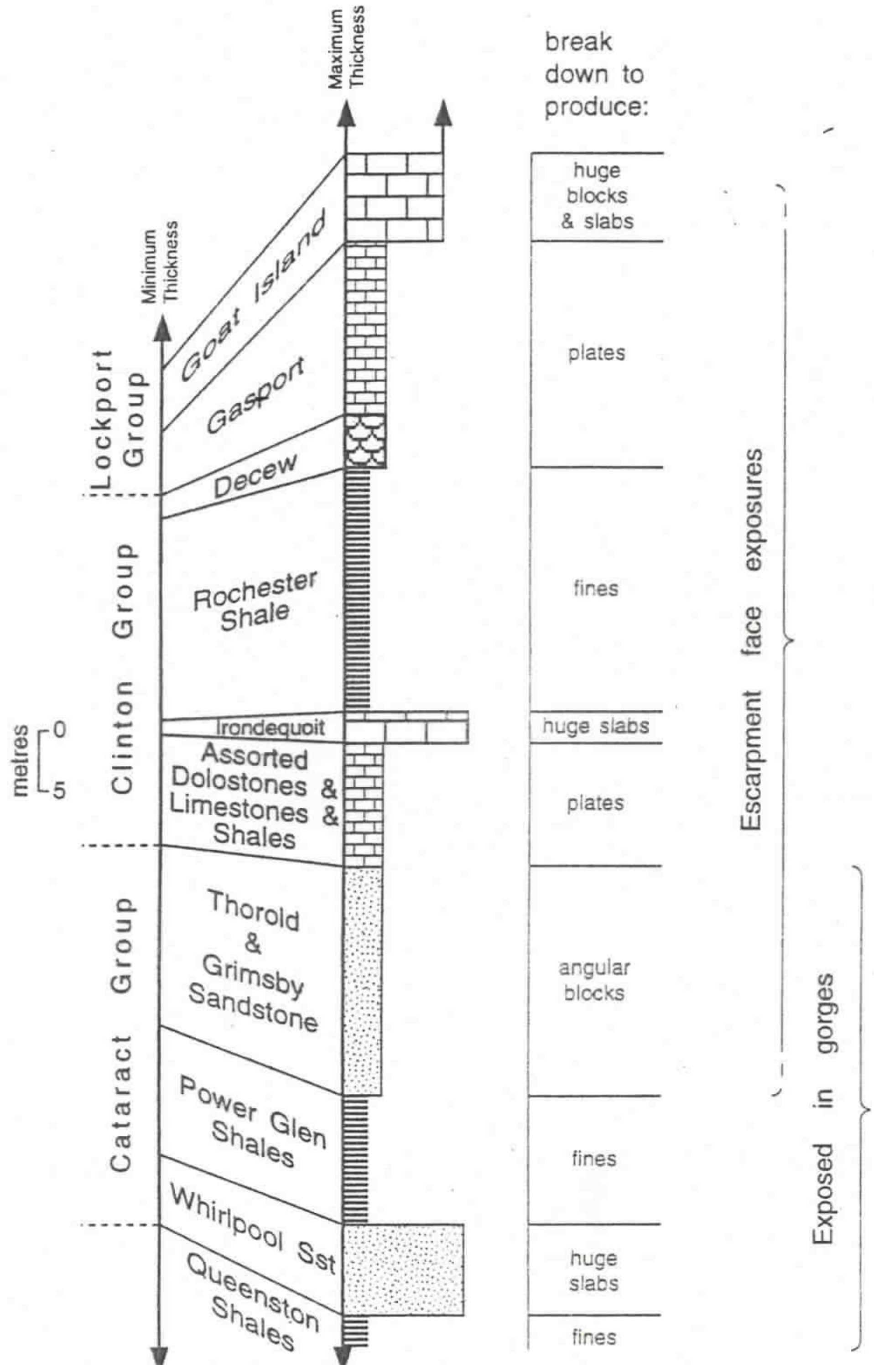


Figure 17: Approximate thicknesses of Niagara Peninsula rocks with maximum and minimum values indicated.