GLACIAL AND ENGINEERING GEOLOGY ASPECTS OF THE NIAGARA FALLS AND GORGE

Parker E. Calkin, Department of Geological Sciences, State University of New York at Buffalo, Buffalo, NY 14214
Thomas A. Wilkinson, U.S. Army Corps of Engineers, Buffalo District, Buffalo, NY 14207

INTRODUCTION

The Niagara River separating Canada and the United States (Frontispiece II) is unusual as compared to other rivers for its (a) short length and (b) discharge stability due to the immense storage capacity of its drainage basin. It is largely supplied by the excess discharge brought into Lake Erie from Lakes Superior, Michigan and Huron. In addition to their stabilizing effect, the Great Lakes trap most of the basin sediment so that the river is essentially sediment-free (Philbrick, 1970). From its mouth at the north end of Lake Erie at 174.4 m (572 ft) the Niagara descends 23.3 m (73 ft) to the brink of the Falls, drops vertically 51 m (167 ft) (Fig. 1), and then descends another 22.6 m (74 ft) in gorge to Lake Ontario at 75 m (246 ft). The mean natural flow is about 5,721 m^3 sec^{-1} (202,000 ft^3 sec^{-1}), and can be increased temporarily by as much as 50 percent due to water surface set up during storms along Lake Erie. However, it is otherwise very stable. Since about 1905, the flow over the Falls itself has been markedly limited by water diversion for hydroelectric power generation. Presently it carries 50 percent of the river's natural flow or about 2,800 m^3 sec^{-1} (100,000 ft^3 sec^{-1}) during tourist hours and only about 25 percent (1,400 m^3 sec^{-1}/50,000 ft^3 sec^{-1}) at other times. About 92 percent of undiverted flow passes over the Horseshoe Falls, 8 percent over the American Falls, and this percentage may have been the average even under precontrol discharges (American Falls International Board, 1974).

The differences in elevation that cause the Falls is related to the presence of the Niagara cuesta (escarpment) that divides the Erie and Ontario basins (Frontispiece I and II). The canyon (gorge) of the Niagara has been cut southward from this escarpment into a section of jointed, gently south-dipping sedimentary rocks capped by the tough Lockport dolostone. The stratigraphy is considered in detail in a subsequent section of this paper and in Brett (1982, this volume).

The modern Niagara River was initiated as a multi-outlet river-lake system following the last retreat of the Last Winconsin ice sheet; the cutting of its deep incised gorge through time is related in various degrees to the changes in drainage controlled by this ice retreat. The ancestral development culminating with a more detailed chronology for development of the Upper Great Gorge is the initial subject of this paper. The second part considers details of the geology in the present area of the Falls and the geologic processes that control stability as well as retreat of the Falls and Gorge as they are revealed in the context of major engineering projects undertaken principally along the east (American) side of the Niagara Gorge. A third section considers the future of the Falls.

DEVELOPMENT OF THE ANCESTRAL NIAGARA

The generalities and many details of the geology and evolution of the Niagara River drainage system have been presented and updated successively by a number of authors since early work by Charles Lyell (1838-1842) and James Hall (1842). Such accounts are found in studies by Gilbert (1891, 1895, 1907), Grabau (1901), Spencer (1907), and particularly Taylor (Kindle and Taylor, 1913; 1933). Much of this section is taken freely from a recent synthesis and study of Calkin and Brett (1978). The Late Wisconsin glacial events leading up to the formation of the modern Falls and Gorge are considered by Calkin (1982, this volume).

The Lake Tonawanda Phase

Initiation of the Niagara River occurred following the Late Wisconsin, Port Huron Stadial as the ice margin retreated from western New York for the last time. In this area, the orientation of striations, bedrock fluting, and drumlins indicate that the ice had moved accross the area from the northwest (see Kindle and Taylor, 1913). Glacial retreat in the Erie Basin like those in the rest of the Great Lakes drainage was down the regional slope and therefore accompanied by a generally lowering succession of large proglacial Great Lakes (Calkin, 1982, this volume). Glacial Lake Dana, the last and lowest of this succession, formed in the northern part of the Erie Basin and southernmost Ontario Basin as the ice margin backed northward from a position near the Albion-Rochester Moraine along the Niagara Escarpment (Frontispiece II).

Lake Dana drained westward through channels at Syracuse and existed only long enough to form weak beach ridges at about 205 m (673 ft) near Buffalo before continuing retreat opened lower outlets to the east. This event led to emergence of the Niagara Escarpment and consequent formation of Early Lake Erie. This discharged via the incipient Niagara River across the emergent escarpment to Glacial Lake Iroquois which formed almost contemporaneously in the Ontario Basin. Lake Iroquois drained into the Mohawk River over a threshold near Rome, New York and thence to the Hudson Valley. Stabilization occurred just before a minor glacial readvance to the Carlton Moraine along the present south coast of Lake Ontario (Muller, 1977a).

The time for inception of these events and the Niagara River is not bracketed closely by reliable radiocarbon dates; however, those available suggest formation about 12,300 yr B.P. (Calkin and Brett, 1978; Karrow, 1981).

Early Lake Erie received the discharge from Glacial Lake Algonquin in the Hudson Basin via Port Huron (through Lake St. Clair and Detroit River) and was very narrow; its outlet near Buffalo was depressed as much as 42 m (138 ft) from that of the present (Lewis, 1969). Former major outlets cut across the Niagara Escarpment west of Niagara Falls in the preglacial ? Erigin Valley (Karrow, 1973), or the St. Davids Gorge (Figs. 1 and 2) were drift-filled. The outflow of Early Lake Erie therefore flooded the lowland between Onondaga and Niagara escarpments forming the shallow, multi-outlet Lake Tonawanda (Frontispiece II).

Lake Tonawanda was really a river-lake extension of the upper Niagara River; it stretched 93 km (58 mi.) eastward at its high strand-producing level of $\sim$178.3 m (585 ft) near Niagara Falls and averaged about 10 m (30 ft) in depth. Sediments are typically mottled, buff, silty fine sands, sparsely fossiliferous (see Calkin and Brett, 1978) and up to 3 m ($\sim$10 ft) thick. Finer sediment was carried from Lake Tonawanda with the general outflow via spillways cut through the Niagara escarpment to Glacial Lake Iroquois at Lewiston, and farther east at Lockport, Gasport, Medina, and Holly, respectively (Kindle and Taylor, 1913; Frontispiece II).

At least one of these bedrock spillways had been cut previous to this outflow. Clayey sand and gravel described from deep borings in the lower portion of the Lockport spillway is interpreted as till (Calkin and Brett, 1978).

During initial stages of the Niagara River, Lake Tonawanda discharged to the low, short-lived Newfane phase of Glacial Lake Iroquois; this built weak beaches 26 m (85 ft) above the present Lake Ontario level at Lewiston (Kindle and Taylor, 1913). Wood from the Lockport site (Frontispiece II) dated at 12,100 $\pm$ 400 yr B.P. may have been washed across the gravelly delta of the Lockport spillway during Newfane time (Miller, 1973). Uplift subsequently raised Lake Iroquois 12 m (39 ft) to its most persistent "Lewiston" phase. The main Iroquois strand is characterized by a very well developed and continuous storm beach ridge about 6 m (20 ft) high.

Lake Iroquois may have drained about 12,000 to 11,000 yr B.P. but its duration is difficult to determine because of uncertainties in the radiocarbon dates from shell materials (Karrow, 1981). Iroquois was succeeded by several post Iroquois proglacial lakes and subsequently by the low, Admiralty phase of Early Lake Ontario as concurrent ice margin retreat allowed the outflow to move respectively from the Mohawk Valley (thence Hudson Valley), to the Covery Hill outlet north of the Adirondacks, and then to the Champlain Sea in the St. Lawrence Valley. The position of the ice front during this period and the timing and verification of outlet routes from the Ontario Basin may have controlled in a more complicated manner by the Valders (Great Lakean or Two Rivers) advance allowing fluctuation of Ontario waters through more than one sequence of >150 m (Gorman and others, 1978; see also Gadd, 1980 and Karrow, 1981).

The main channel of the Lewiston spillway system headed 1,200 to 2,000 m (4,000 to 6,500 ft) north of the American Falls and eventually became the main "Niagara River channel" as differential isostatic uplift toward the northeast caused the eastern outlets to give way successively to those in the west closer to the Lake Erie outflows. Dated wood from the interface of gravelly clay of Lake Iroquois and overlying wood marl depsoits at the lower end of the Lockport spillway indicates that major sediment discharge and most water flow through this spillway had ceased by about 10,920 $\pm$ 160 yr B.P. and that Lake Iroquois had drained (Calkin and Brett, 1978).

Fluctuation of the Upper Great Lakes and Niagara River Discharge

As the Lewiston spillway (future Niagara Gorge) was receiving a successively greater share of the Niagara discharge through uplift of the eastern outlets, Lake Erie was also rising, causing an increase in lake size. Likewise, changes in the position of the ice margin to the north and west caused discharges into Lake Erie and hence the Niagara via Port Huron and the Huron Basin to change or cease entirely (see maps in Hough, 1966; Prest, 1970). A reduction of 80 to 90 percent must have occurred as ice retreat opened the Kirkfield Ontario outlet to the Trent River and allowed waters of Glacial Lake Algonquin in the Huron Basin to drain directly into the post-Iroquois lakes or Early Lake Ontario. Complete bypassing by Huron and western waters may have occurred in one or even two episodes about 11,500 yr B.P. (Karrow and others, 1975; Karrow, 1981). A possible second episode may have occurred following a very brief post-Two Creeks - Valderan advance across the Trent River (Hough, 1963; Fullerton, 1980) before isostatic uplift closed the Kirkfield outlet. Continued ice retreat opened direct eastward discharge to the St. Lawrence basin about 10,400 yr B.P. (Karrow and others, 1975) at North Bay, Ontario. The upper lakes then drained directly through the Ottawa Valley into the St. Lawrence Valley until about 5500 yr B.P. when outlets to the south at Chicago and again at Port Huron became active (Lewis, 1969). Between 4700 and 3700 yr B.P. during Lake Nipissing II stage in the Upper Great Lakes, drainage was shared by only the Chicago and Port Huron outlets; full discharge from the upper lakes returned through the Port Huron-Lake Erie-Niagara River route in post-Nipissing time, about 3700 yr B.P.

Timing of Local Events

Discharge variations through the Niagara and fluctuations of base-level in the Ontario Basin must have affected the rate and manner of Niagara Falls recession as did a multiplicity of other factors (see succeeding successions of this paper). Taylor (Kindle and Taylor, 1913; 1933) proposed a correlation of Gorge sections with lake history (Table 1). This and similar correlations based largely on physical dimensions of the gorge (Fig. 1) are yet unproved and speculative but are at least compatible in part with the recent dated chronologies (Calkin and Brett, 1978; Fullerton, 1980). Some recent studies of the Niagara River throw light on the local timing of gorge development.

TABLE 1 - CORRELATIONS OF GORGE SECTIONS BY TAYLOR (1933)

Glacial Lake Event	Niagara Gorge Section of Event *
Early Algonquin to Kirkfield Algonquin	Lewiston Branch Gorge
Kirkfield Algonquin	Old Narrow Gorge
Port Huron Algonquin	Lower Great Gorge
Termination of Iroquois	Falls at Head of Niagara Glen
Nipissing ** (North Bay open)	Whirlpool Rapids Gorge
Post-Nipissing (similar to present drainage)	Upper Great Gorge

* See Fig. 1.

** This is the Early L. Nipissing-Stanley lake stage of Prest (1970).

Niagara River Gravels. As the Gorge was enlarged by recession of the Falls, the river a few hundred meters above respective cataract positions may have resembled its present aspect above Goat Island. The banks of this ancestral Niagara are terraced and outline a channel much broader than the Gorge. Remnant sands and gravels along this channel (Fig. 3) contain a well-preserved mollusk assemblage in part like that of the present (Letson in Grabau, 1901; Calkin and Brett, 1978). The main pattern of development of the Gorge involved minimal vertical cutting with general headward recession of one major cataract line from the Niagara Escarpment at Lewiston.

At the Whirlpool (Figs. 1 and 3b), radiocarbon dates of 9770 $\pm$ 150 yr B.P. were obtained on unionid pelecypod fragments and 9915 $\pm$ 165 yr B.P. on gastropod shells within the Niagara River terrace gravels along the Gorge walls 88 m above the present river. These suggest that these beds were abandoned by the river about 9800 yr B.P. (Calkin and Brett, 1978). The cataract itself may have been about 800 m downstream from the Whirlpool at this time. The overall average rate of recession to this point may have been on the order of 1.6 m yr^{-1} (if the cutting at Lewiston began about 12,400 yr B.P.).

Dates of 9080 $\pm$ 130 yr B.P. and 9115 $\pm$ 215 yr B.P. obtained on mullosk shells from the upper meter of a Niagara River gravel section capping Goat Island (Fig. 3a) may reflect abandonment of, or shoaling over, this surface resulting from the opening of the Upper Lakes' outlet at North Bay. The North Bay event would have caused a lowering of Lake Erie by 3 to 5 m (10 to 16 ft) and reduction of the Niagara River discharge by as much as 90 percent (Lewis, 1969). The dates above also provide a minimum age for a mastodon tooth recovered from the gravels near Prospect Point by James Hall.

The Lake Tonawanda Deposits. Deposition in the eastern parts of Lake Tonawanda must have ceased during reduction in Lake Erie levels. Wood, dated at 10,450 $\pm$ 400 yr B.P. near an outflow area in the southernmost part, overlies scoured clay and underlies sediments containing mastodon remains (Muller, 1977b). However, Lake Tonawanda was high enough in the eastern (Niagara) area to discharge through a spillway channel immediately east of the city to form Devils Hole plungepool (Fig. 1) after the main cataract had receded past the site, perhaps shortly before 9800 yr B.P. (Calkin and Brett, 1978). Furthermore, Lake Tonawanda waters apparently persisted here even until recent centuries (Calkin and Brett, 1978). The return of full discharge of the upper lakes to the Niagara River in Lake Nipissing time is recorded by a mollusk assemblage dated at 3780 $\pm$ 90 yr B.P. This overlies a scoured glacial lake clay at the Niagara Falls Sewage Treatment Plant (Frontispiece II; Calkin and Brett, 1978).

RATE AND MANNER OF ENLARGEMENT OF THE UPPER GREAT GORGE

The Upper Great Gorge is 3700 m in length and as suggested by Taylor (1933) appears to be the product of the full, post-Nipissing cutting under Great Lakes outflow similar to that of the present. This may be supported at least in part by comparison of its mean rate of cutting with that of the historic data. The mean recession rate must have been on the order of 0.8 or 1.0 m yr (3.2 ft yr^{-1}) for the historic period 1842 through 1905 (International Joint Commission, 1953, p. 14) before major man-made water diversions. However, a rate of 1.1 m yr^{-1} (3.6 ft yr^{-1}) has been determined for the total years of record (1670 through 1969, American Falls International Board, 1974; Fig. 3). Projection of these rates indicates that recession past the American Falls and separation of flow into the two channels may have occurred about 600 years ago.

Analysis of the historic rates of recession by the International Joint Commission (1953) suggested that the average recession of the Horseshoe Falls had decreased from 1.28 m yr^{-1} (4.2 ft yr^{-1}) between 1842 and 1906, to 3.2 ft yr^{-1} (0.98 m yr^{-1}) between 1906 and 1927, and to 2.2 ft yr^{-1} (0.67 m yr^{-1}) from 1927 to 1950. They initially attributed this to three main causes including: (1) the southerly dip of the Lockport Formation; (2) the southward thickening of the Lockport cap rock from 6 m (20 ft) at Lewiston to 23 m (80 ft) at the Falls; and

(3) diminishing discharge of the river as a result of increased diversion for hydroelectric power. However, more detailed analysis of historic data (Philbrick, 1970) and that from soundings in the Upper Great Gorge indicate that the rate of retreat has been much more variable than this suggests despite nearly uniform flows and continuous bedrock materials. Furthermore, Philbrick (1970, 1974) has argued that the planimetric configuration of the Falls may be as great or of greater control on recession than factors mentioned above. His ideas relative to retreat of the Horseshoe Falls are summarized below.

Philbrick maintains that there are three stages of the horizontal configuration of the Falls. The vertical cross wall is an unstable form which progresses to the horizontal arch, the most stable form (Fig. 4). Recession will be slow during the arch stage and deep plunge pools will be produced (Fig. 1). This stage in turn may be "broken down into" the notched stage (Fig. 4) when the highest stresses and greatest strains are generated. The notch stage then coincides with the highest rates of recession * and with shallow plunge pools. Model studies (Philbrick, 1970) show that stresses during the notch configuration may be three times those that occur during times when the crest is arched. Depths of the plunge pools are therefore inversely related to the rate of retreat.

Comparison of bottom surveys in the Upper Great Gorge between 1842 and 1966 (Fig. 4) confirms this hypothesis and shows that recession rates of the Horseshoe Falls during existence of a horizontal arched crest may reach 19 ft yr^{-1} (5.8 m yr^{-1}). The rate of present arch reaches about 2.5 ft yr^{-1} (0.76 m yr^{-1}) (Philbrick, 1974, p. 94). In addition, instead of having a uniform downstream slope as might be expected if the Horseshoe retreated at a unifrom rate, soundings in the Maid of the Mist Pool (in the Upper Great Gorge) display a series of "basins" or plunge pools separated by highs which are progressively lower in elevation in the upstream direction (Fig. 1). This profile reflects "an intermittent recession at the progressively slower rate" (1974, p. 94). Philbrick (1970, 1974) has correlated the basins with horizontal arches and long stands, the highs with horizontal notches, and relatively high stresses, and faster recession. The joint spacing on the Gorge walls at Prospect Point (Fig. 4) and Goat Island reflect indications on the bottom profile that suggest notch retreat with high stress oposite Prospect Point and broad arch retreat past the upstream side of the American Falls near Goat Island.

* Also recognized by Gilbert (1907) and Kindle and Taylor (1913).

ENGINEERING GEOLOGY OF THE AMERICAN AND HORSESHOE FALLS

Several engineering geology studies have been undertaken in the area of Niagara Falls on both sides of the border. Three of the more recent published reports concerning the American side include those of Dunn (1954), Acres American, Inc. (1972), and the American Falls International Board (1974). The second author directed the geotechnical aspects of the latter study; therefore, much of this section is taken from the 1974 report on the preservation and enhancement of the American Falls and the Terrapin Point flank of the Horseshoe Falls (SI values added for this paper).

Stratigraphy and Structure

The face of the American Falls (Fig. 6) and the Horseshoe Falls is formed in the Lockport and Rochester formations (Table 2) *. The Lockport Formation is mainly a dolomite. The Oak Orchard through the DeCew members are present at both Falls and appear to be fairly consistent although reef structures cause irregularities in the contacts between the Goat Island and Gasport members. The Rochester Formation, mainly a laminated to blocky dolomitic shale, supports the Lockport Dolomite. It has been divided into six zones. Interbedded limestones, dolomites, sandstones, and shale underlie the Rochester Shale. In general, the Irondequoit, Thorold, and Grimsby formations are resistant units at the American Falls and support talus.

Stratigraphic contacts at the Horseshoe Falls are about 3 m (10 ft) lower in elevation than at the American Falls because of the regional dip. For a generalized section of rocks in the vicinity of the Falls see Table 2.

The strata dip approximately 1/2° to the south and are relatively undeformed with only minor folding.

Joints are present in all formations. A preliminary survey (American Falls International Board, 1974) of the near regional area of the Falls indicated joints are oriented N77°E and N7°W as major joints. These were classified as shear joints. Significant horizontal stresses are present in the rock. There are a number of reported cases of load releases due to excavation at major construction projects in western New York (Rose, 1951; Feld, 1966; American Falls International Board, 1974). Movement has also been attributed to rebound from glacial loading and unloading.

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* See Brett (1982, this volume) for brief explanation of varying stratigraphic terminology used in the Niagara Gorge. The term "Formation" is used in the American Falls International Board Report (1974) where traditionally lithologic terms have often been used in standard geologic literature (e.g., Whirlpool Formation vs. Whirlpool Sandstone in the formal sense).

TABLE 2. GENERALIZED SECTION OF PALEOZOIC SEDIMENTARY ROCKS IN THE AMERICAN FALLS VICINITY. FROM AMERICAN FALLS INTERNATIONAL BOARD (1974, TABLE C2)

System	Series	Group, formation, member or zone			Thickness (ft.)	Lithology
Silurian	Niagaran	Lockport Group	Lockport Formation	Oak Orchard member	70±	Dolomite, medium-gray to medium dark-gray; thin- to thick-bedded, numerous irregular shale and stylolitic shale partings, slightly argillaceous; chert nodules and white dolomite crystals are common. The member is finely crystalline and sugary textured. Vugs commonly are filled with calcite, gypsum and sphalerite. Stromatolite domes are present. The rock is moderately hard.
				Eramosa member	14	Dolomite, medium-gray to grayish-brown; thin- to medium-bedded with numerous bituminous and carbonaceous stylolitic shale partings and stylolites. White porous chert and coarsely crystalline dolomite masses are common; gypsum, anhydrite, fluorite and sphalerite occur in lesser amounts. The member is very finely crystalline and sugary textured. The rock is moderately hard. Occasional vugs are filled with calcite and gypsum.
				Goat Island member	26	Dolomite, medium-gray in upper, dark-gray in middle and light-gray to light tannish-gray in the lower part, occasionally mottled; massive in upper and lower part and thin- to medium-bedded in the middle, slightly to very argillaceous with abundant shale and stylolitic shale partings in the middle. The member is finely to medium crystalline and sugary textured. The lower part is coarsely crystalline, pitted and vuggy; the vugs are occasionally filled with secondary dolomite crystals. The rock is moderately hard.
				Gasport member	18	Dolomite to dolomite-limestone, light- to medium-gray; massive with abundant stylolites and discontinuous shale partings throughout; slightly argillaceous in the upper and conglomeratic with pebbles of DeCew lithology in the base. The member is finely to coarsely crystalline and sugary textured. The rock is moderately hard. Vugs and pits are filled occasionally with gypsum.
				DeCew member	10	Dolomite, medium- to dark-gray; thin- to medium-bedded with an occasional thick bed; argillaceous with wavy irregular shale partings that contain well developed slickensides; stylolites and stylolitic shale partings are common; occasionally masses and nodules of gypsum occur. The member is finely crystalline to crystalline with a well-cemented mosaic texture. The rock is moderately hard. Outcrops contain a "flow" or "enterolithic" structure.
		Clinton Group	Rochester Formation	zone 1	1-2	Shale, medium dark-gray; laminated to platy, slightly dolomitic, dense and moderately hard. This zone is a transition from the Rochester below to the DeCew above.
				zone 2	13±	Shale, medium dark-gray to dark-gray; laminated to blocky and contains discontinuous partings and bands of light-gray dolomitic limestone. Clay minerals are illite, chlorite, kaolinite and traces of montmorillinite; the zone also contains scattered pyrite and gypsum masses near the base. Microcrystalline dolomite is interspersed with finely crystalline illitic clay and quartz. The rock is moderately hard.
				zone 3	6±	Dolomitic shale and shaly dolomite, medium dark-gray to dark-gray; thin-bedded in upper and basal, massive in the middle; shale partings occur in the upper and lower parts. Illitic clay, traces of chlorite, kaolinite and silt size quartz grains are dispersed throughout the zone. The rock is dense, contains very few pores, and is moderately hard.
				zone 4	25-29	Shale, medium- to dark-gray; laminated to blocky and contains numerous discontinuous partings and bands of light-gray dolomitic limestone; gypsum partings are abundant. Nodules of calcite and gypsum occur occasionally. The clay minerals are illite, chlorite, kaolinite and mixed layered clay. The zone has a dense, microcrystalline texture. Portions of the zone are fairly well cemented with dolomite; other parts are more shaly and rapidly fracture upon drying. The rock is moderately hard.
				zone 5	6-10	Shale, medium- to dark-gray; laminated, dolomitic and contains occasional gypsum partings, white calcite nodules, numerous discontinuous partings and bands of limestone and thick beds of shaly dolomite. Silt size quartz grains are scattered throughout. Clay minerals are illite, chlorite, kaolinite and mixed layered clay. The texture of the zone is microcrystalline. The rock is moderately hard.
				zone 6	4-5	Shale, medium- to dark-gray; laminated to blocky; contains light-gray laminae and bands of calcite and dolomite. The blocky shale contains gypsum partings. Quartz grains are common; pyrite and marcasite occur with carbonaceous matter as a replacement of organic matter. The clay minerals are illite, chlorite and kaolinite. The rock is moderately hard.
			Irondequoit Formation	Unnamed member	6-9	Limestone, light-gray with pinkish tint, medium-bedded to massive with frequent wavy irregular green or black shale partings near the top. The member is coarsely crystalline, The rock is moderately hard. A few vugs and small pores are present.
				Rockway member	10-11	Dolomite, varies from light- to medium-gray in the upper part to brown in the middle and brownish-gray at the base; thin- to thick-bedded in the upper, massive in the middle and thin-bedded at the base; argillaceous to very argillaceous at the base. Dark-gray shale partings and a few gypsum nodules occur throughout the member. The member varies from dense to finely crystalline and has a sugary texture. The rock is moderately hard.
			Reynales Formation	Hickory Corners member	2-3	Unconformity Limestone, light- to medium-gray; argillaceous, calcitic and highly siliceous; numerous wavy, dark-gray shale partings and bands produce a pseudonodular appearance. The texture of the member is very finely crystalline to dense. The rock is moderately hard.
			Neahga Formation		6	Shale, dark greenish-gray; platy to fissile with a waxy appearance; shaly sandstone at base. Masses of pyrite and gypsum partings occur along the bedding planes; calcite and dolomite occur in small amounts and quartz is the most abundant non-clay mineral. Illite is the dominant clay mineral with lesser amounts of chlorite, kaolinite and mixed layered clay. The rock is soft and flakes readily during wet-dry cycles. Slickensides are present.
		Medina Group	Thorold Formation		9	Sandstone, light-gray to greenish-gray; medium-bedded to massive; irregular green shale partings occur throughout. The sandstone is orthoquartzitic. The texture of the formation is very fine grained. Silt size to fine grained quartz particles are cemented with secondary silica. The rock is hard.
			Grimsby Formation	zone b	8	Sandstone, pink to reddish-brown; thin- to thick-bedded, hematitic, calcareous. The texture varies from fine to medium grain. The rock is moderately hard to hard. A weathered zone frequently occurs at the top of the formation.
				zone a	43	Siltstone and sandstone with interbeds of shale, variegated from red to pale green; pink, white or mottled siltstone or sandstone with red shale and red sandstone interbeds. Gypsum partings occur in shale beds. The sandstone is fine- to medium-grained and well-cemented. The siltstone and shale vary from soft to moderately hard.
			Power Glen Formation		34	Shale with siltstone beds and stringers of silty limestone and dolomite; dark-gray to grayish green shale and siltstone, and light-gray limestone and dolomite; laminated to banded. Quartz is the most abundant non-clay mineral. Clay minerals consist of illite, chlorite and small amounts of montmorillonite and mixed layered clay. The rock is slightly soft to moderately hard.
			Whirlpool Formation		18	Sandstone, light-gray to white; medium-bedded and cross-bedded; fine- to medium grained. The quartz grains are frosted and well rounded, and are well cemented by secondary silica. Feldspar grains altered to kaolinite are abundant. Occasional green shale inclusions and chloritic shale partings occur throughout. The rock is slightly soft to moderately hard.
Ordovician	Cincinnatian	Richmond Group	Queenston Formation		100±	Unconformity Shale (technically classified as a claystone) reddish-brown (ferric) shale with interbeds and nodules of green (ferrous) shale; massive to blocky. The shale is silty and is cemented by dolomite and calcite. Scattered gypsum nodules occur throughout; quartz is a common constituent. Clay minerals are illite, chlorite, kaolinite, montmorillonite and mixed layered clay. The shale is highly compacted and moderately hard. Numerous small, high angle slickensides are stained with iron oxide.
			Total		429±	

Note:

The stratigraphy is compiled from Zenger (1965 and 1966), Fisner (1966) and Kilgour (1966), from stratigraphic studies by U.S. Army Engineer District, Buffalo New York and from petrographic descriptions by U.S. Army Engineer Division, Missouri River. The Rochester Formation zonation was developed for this study by the Buffalo District.

In the Lockport Dolomite of the American Falls the major set of high-angle joints (primary shear set S_1) trends N70°E to N80°E and penetrates into the Goat Island Member. The S_1 joints are generally straight, spaced 3 to 24.4 m (10 to 80 ft) apart, and have traceable lengths up to 39.6 m (130 ft). A variable, complimentary shear set (S_2) has an approximate range of N to N30°E. Bisecting the angle between these sets results in a principal stress direction of about N45°E. This is in general agreement with the principal high horizontal stress shown by overcoring (N34°E $\pm$ 30° and N54°E $\pm$ 12°). There is a minor concentration of joints between N40°E to N50°E which is parallel to the maximum stress direction; this set has been classified as tension set (extension) T_1. There is a weak T_2 set (release) perpendicular to the maximum stress direction oriented N40°W to N60°W. In addition to high-angle joints, several bedding plane joints were found that are generally open across the face. For the general location of joints in the Lockport Dolomite on the dewatered riverbed see Figure 5.

The joints in the Rochester Shale at the American Falls vary from N10°W to N80°E, generally dip toward the Gorge (approximately northwest), and have spacings from 0.06 m (0.2 ft) to several tens of ft. The joints on the face have variable vertical penetration and quite often terminate or become offset at the more massive dolomitic Zone 3. However, some joints extend through the entire Rochester Shale. Joint openings vary from closed to open more than .3 m (1 ft). The exposed joint planes are usually curvilinear. The frequency of joints decreases with distance from the face (Fig. 6). In some areas joints are present at least 34.1 m (112 ft) back from the face. The joints generally parallel the trends of the American Falls face and are classified as stress release joints originating from tensile stresses directed into the Gorge. Jointing in underlying formations at the American Falls is known from borings and a few outcrops; however, there are not enough data to determine joint sets.

The prominent joints in the Rochester Shale at the Horeshoe Falls trend N50°E to N60°E, N70°E to N80°E, and N40°W to N50°W and probably reflect the change in direction of recession of the Horseshoe Falls. Frequency decreases with distance from the face. The joints appear to be stress release joints and in some areas are present 27.4 m (90 ft) back of the cliff face.

Two thrust faults were found on the face of the American Falls and are located entirely within the Rochester Shale. One fault is near the flank of the 1931 rockfall area and the other is located just downstream of Luna Island. Both faults have a very small vertical displacement.

Engineering Properties

Consideration of repair for the preservation of the American Falls required a thorough study of the physical strength characteristics of the rocks that make up the Falls escarpment. Testing of the rocks was performed by the Missouri River Division Laboratory (1971) to establish criterion upon which the repair could be based. The conclusions from the report are summarized below.

The five members of the Lockport Formation are dense, hard, low absorptive rock with a unit weight of 26.2 kN/m^3 to 27.2 kN/m^3 (167 to 173 pcf). They are highly durable and, as shown by the following test results, have adequate strength for most engineering consruction: tensile strength 2,756 to 9,646 KPa (400 to 1,400 psi); unconfined compressive strength 117,130 to 192,920 KPa (17,000 to 28,000 psi); Tangent Young's modulus 41.3 to 75.8 X 10^6 KPa (6 to 11 X 10^6 psi); and Poisson's Ratio 0.25 to 0.37. Angle of internal friction ranges from 59 to 68 degrees and cohesion intercept values vary from 9,646 to 17,914 KPa (1,400 to 2,600 psi). Frictional resistance of smooth sawed joints averages 0.60 and is 0.73 for the moderately rough natural joints. Cohension intercept values of 344.5 to 2,756 KPa (50 to 400 psi) were obtained for the natural joints; the value was largely dependent upon the surface roughness.

The Rochester Formation, comprised of six zones, is quite variable in composition and structure. Carbonate content, mostly as dolomite ranges from 34 to 67 percent by weight of the rock. High unit weights of 26.5 kN/m^3 to 27.1 kN/m^3 (168.5 to 172.6 pcf) and low absorption, 1.5 to 2.3 percent, indicate a highly compacted, well-cemented shale. All of the zones are very susceptible to deterioration in freezing-and-thawing. Additionally, all but Zone 3, a shaly dolomite, also break down almost completely in the wetting-and-drying test.

The Rochester Shale is very weak in tension normal to the bedding (34.5 to 1,309.1 KPa) (5 to 190 psi); however, it is 10 to 20 times as strong in a direction parallel to it. Unconfined compressive strength is variable ranging from a low of 19,774.3 KPa (2,870 psi) to a high of 88,329.8 KPa (12,820 psi). Average strength for the more shaly beds is about 31,349.5 KPa (4,550 psi) with Zone 6 being the weakest at about 2/3 of this value. The shale has a tangent Young's Modulus of 2.1 to 25.5 X 10^6 KPa (0.3 to 3.7 X 10^6 psi) and a Poisson's Ratio of 0.30 to 0.50 for most of the zones. In the range of 385.8 to 1,378 KPa (56 to 200 psi) confining pressure, the Mohr strength envelopes of the shale zones have slopes of 60 to 73 degrees and cohesion intercepts of 344.5 to 3,927.3 KPa (50 to 570 psi). The smooth sawed joints of the shale have greater frictional resistance, averaging about 0.75, than the moderately rough natural joints, 0.49. Values of cohesion intercept range from 172.3 to 2,411.5 KPa (25 to 350 psi) for the natural joints. Direct sheer tests on bedding planes gave an average sliding friction angle of 26 degrees. Illite and chlorite with a small amount of mixed layered clay and kaolinite are the principle clay minerals present in all of the shale zones.

Both the limestone and sandstone formations of the underlying beds have similar strength characteristics as the Lockport Dolomite. The Neahga Shale is the weakest shale with an unconfined compressive strength of 5,167.5 KPa (750 psi). It is a highly fissile, illitic rock with a frictional resistance of about 0.31 to 0.60 derived by direct shear on bedding planes. These friction values reduce to 0.09 at 1,378 KPa (200 psi) normal stress indicating a low shear strength material.

Contemporary Processes

Ground Water. Open fractures in the Lockport Dolomite provide lateral and vertical seepage paths to the face and to underlying formations. There is a continuous recharge from the river to the permeable zones. The Lockport Dolomite generally has low permeability except in areas where structural defects occur. Several boreholes accepted 18.9 to 53 cubic decimeters/min (5 to 14 gal/min) at member contacts or at partially detached (translated) zones near the face. Seepage occurs in the cliff walls adjacent to the Falls; the seepage occurs along horizontal open bedding planes intersected by major joints in the Lockport Dolomite. Piezometer studies indicated that seasonal fluctuations generally range from 0.3 to 1.8 m (1 to 6 ft), piezometric levels are influenced by the level of flow in the river, and winter blockages of drainage are possible.

Pressure tests and dye tracer tests indicated that the Rochester Shale generally is tight except near the face where there are concentrations of high-angle stress release joints. Very small quantities of water were observed seeping along the Lockport-Rochester contact at Prospect Point.

Pressure tests indicated that underlying units contain some zones with moderate permeability.

Weathering and Erosion. The rock at the Falls weathers and erodes because of effects from flowing and falling water, from seasonal ice buildup, from wetting and drying (in some areas), and from stresses within the rock. The Lockport Dolomite is more resistant to erosion and weathering than the Rochester Shale. Solution action of water was evident from cores in which there were weathered, stained, widened, and sometimes mineralized (gypsum and calcite) fractures and joints. The Rochester Shale, except for Zone 3, cannot stand repeated wet-dry cycles. After 10 cycles the losses during wet-dry testing ranged from 85 to 100 percent (except for Zone 3). Ice-jacking and freeze-thawing are significant processes which contribute to erosion. Accumulations of ice have varied from local accumulations to complete freezing of the American Falls. Freeze-thaw tests showed losses as a result of fragmentation ranging from 0.5 percent to 20 percent for the Lockport Dolomite and from 32 percent to 75 percent in the Rochester Shale.

Undermining. Undermining is the result of progressive surface deterioration from various modes of weathering, collapse of weakly supported masses, and the buckling of vertically jointed masses of rock from loading.

At the American Falls, undermining is most pronounced in the 1931 rockfall area (Fig. 7). There, a segment of the face, about 36.6 m (120 ft) wide, is recessed a maximum of 9.1 m (30 ft). In profile, undermining actually begins in the lower part of the Goat Island Member, but is deepest in the Rochester Zone 2.

At the Horseshoe Falls (Terrapin Point) the Lockport Dolomite generally is undermined; the maximum undermining which is commonly found, is about 4.6 m (15 ft).

Talus Accumulation. Rockfalls have resulted in huge piles of talus at the American Falls. The volume of talus is estimated to be 214,200 m^3 (280,000 yd^3). The resistant Irondequoit, Thorold, and Grimsby formations form ledges that underlie the talus accumulation at the American Falls. Most of the talus consists of blocks of Lockport Dolomite. The sizes of 130 of the largest accessible blocks varied from slightly less than 90,718.5 kg (100 tons) to greater than 2,177,243.3 kg (2,400 tons). Boulders about 0.9 m (3 ft) or smaller in diameter can be moved and reduced by the tumbling action (abrasion) of falling water at the American Falls.

The talus beneath the Horseshoe Falls at the central apex area is ground up and dispersed by the flow; there is no visible accumulation comparable to that at the American Falls. The talus mound from the 1934 rockfall adjacent to Terrapin Point is the only significant accumulation.

Rockfalls, Failure Mechanisms, Stability. The earliest reference to rockfalls found is a passage from Lyell (1845) quoted in Dow (1921) which reported the sudden descent of huge rock fragments of undermined limestone at the Horseshoe Falls in 1828 and another at the American Falls in 1818. At the American Falls other rockfalls of significant size occurred in 1931, July 1954, and December 1954 (Fig. 7). Rockfalls of less significant size occurred in 1907, 1920, 1967, and 1974. At the Horseshoe Falls other rockfalls of significant size occurred in 1823, 1846, 1850, 1852, 1882, 1889, 1905, 1934, 1936, 1937, 1963 and 1981. Numerous intermittent and sometimes unnoticed rockfalls of generally lesser significance have also occurred at both Falls and flank areas.

Since the separation of the American and Horseshoe Falls about 600 yr ago, the American Falls has retreated on the order of 61 m (200 ft), while the Horeshoe Falls has retreated about 762 m (2,500 ft). The results of surveys since 1842 show that the American Falls has undergone drastic changes attributable to massive rockfalls beginning in

1931. The recession has been sporadic. The general rate of recession of the American Falls in 600 years is about 0.09 m yr^{-1} (0.3 ft yr^{-1}). This is considerably slower than the 3.6 ft yr^{-1} (1.1 m yr^{-1}) rate of recession obtained for the Horseshoe Falls between 1678 and 1969 mentioned in a previous section of this paper (see Fig. 4).

A computerized two-dimensional analysis of the Niagara Falls area using the finite element method was performed (Fairhurst, 1969) in order to determine the influence of the direction of the known regional stress field in western New York on the stability of the Falls. The analysis indicated that a lateral compressive stress parallel to the Niagara Gorge tends to develop a concentrated compression behind the arcuate crestline of the Horseshoe Falls. Those compressive stresses tend to close the joints in the Lockport Dolomite stabilizing the center portion and thereby preventing the fall of large rock fragments. However, in the region of the American Falls, the analysis indicated that at promontories in the crestline, such as at Prospect Point, there would be a tendency for tensile stresses to develop somewhat behind the crest acting to open vertical fractures parallel to it. Compression parallel to the Gorge would thus tend to contribute to failure of rock-mass in promontories along the Gorge, particularly where water under pressure could enter the fractures.

At the American Falls measurements of the horizontal stresses were made in two shallow vertical holes located 54.9 and 176.8 m (180 and 580 ft) back from the crestline (Fig. 5). Results indicted that significant horizontal stresses exist in the Lockport Dolomite and act in a generally NE-SW direction (parallel to the Gorge). At the 176.8 m (580 ft) location, the horizontal stresses had an average magnitude of +6,890 KPa (+1,000 psi) (compression) and -68.9 KPa (-10 psi) (tensile) while at the 54.9 m (180 ft) location the stresses had an average magnitude of +5,994.3 KPa (+870 psi) (compression) and -2,273.7 KPa (-330 psi) (tensile). The high tensile stress near the Gorge wall is particularly significant since the average tensile strength of the Rochester Shale parallel to the bedding is only 1,446.9 KPa (210 psi). These high tensile stresses probably extend down into the underlying Rochester Shale and explain the development of stress release joints in the shale.

There are at least two modes of failure at the American Falls (Fig. 8). The classical mode of failure occurred in January 1931, when erosion of the Rochester Shale undermined and caused failure of the overlying Lockport Dolomite along existing high-angle joint planes. The jointed cap rock could no longer support its own weight and failed.

Another mode of failure occurred in July 1954. That failure occurred at the wetwall-drywall contact at Prospect Point. Prior to the rockfall, photographs indicate that there was some undermining of the cap rock. Since the landward depth of the failed mess 39.6 m (130 ft) far exceeded the depth of undermining, the mode of failure was something other than ordinary gravity collapse. Close evaluation of photography taken during the rockfall indicate a slight down-dropping of the top of rock prior to its toppling. The down-dropping probably was the result of shearing within the Rochester Shale. The main features contributing to this rockfall appear to have been: (1) the open joints in the Lockport cap rock and possibly in the Rochester Shale, which created the weak zone for the back limit of the rockfall; (2) the unbuttressed cliff face; (3) the failure plane at the bottom of the block (assumed to be the Rochester Shale); and (4) the hydrostatic pressure.

Large rockfalls are likely to occur in the future. One of the most significant areas with questionable stability at the American Falls is Indian Head Point (Fig. 7). It is a detached block of rock about 53.3 m (175 ft) long by 30.5 m (100 ft) wide with open vertical fractures extending into the shale below. The block is considered to be just barely stable. If it collapsed, it could drag down large amounts of adjacent rock. At Terrapin Point, a significant mass of rock adjacent to the river flow and in front of the viewing area is failing. The structural conditions were identified in 1972 and the outer portion of the Terrapin Point viewing area was fenced off by Park authorities. An earthquake induced failure here could involve a significant portion of Terrapin Point.

Preservation, Enhancement, and Remedial Work

The most recent comprehensive study of the Falls (American Falls International Board, 1974) considered the measures necessary to preserve or enhance the beauty of the American Falls at Niagara as well as public safety at the flanks of the American Falls and at the Terrapin Point flank adjacent to the Horseshoe Falls.

The Niagara Frontier State Park and Recreation Commission completed a contract recently for instrumentation and drainage of the viewing area at Terrapin Point and also completed a study of possible rock removal and restoration of the viewing area at Terrapin Point. The Commission removed overhangs at Luna Island in 1955 and performed additional remedial work there (installation of rock bolts, tendons, and drain holes) in 1972.

OTHER MAJOR ENGINEERING PROJECTS ALONG U.S. SIDE OF THE NIAGARA GORGE

The Niagara River has been used for power purposes for over 200 years. Hydroelectric power was produced at Niagara Falls as early as 1880. The first large scale output of commercial power at Niagara Falls began in 1895 (Adams Station). Around the turn of the century advances in electric power development made practical the construction of power plants at the bottom of the Gorge (Schoellkopf Stations). The Robert Moses Niagara Power Plant was completed in 1963 and at the time was one of the world's largest with an installed capacity of 1,950,000 kilowatts.

Schoellkopf Power Plant Failure

On June 7, 1956, a massive rockfall destroyed Schoellkopf Powerhouse Stations 3B and 3C and damaged 3A near the current site of the Schoellkopf Geological Museum. The powerhouse stations had been excavated in the Grimsby Sandstone at the base of the Gorge wall. The rockfall was progressive; it started at the south end and worked northward. Prior to the rockfall, large leaks of water emerged from the cliff face. Apparently no report which included an analysis of the failure was ever published. From the limited information available, it appears that removal of rock at the base of the cliff, possible weak shale zones at the base of the failure, open joints and fractures (some blasting induced?) back of the cliff face which permitted high joint water pressures to develop, and a source of recharge of water (an unlined canal) were the major reasons for the failure. The triggering cause for the failure may have been the blockage of drainage as a result of grouting programs performed just prior to the failure. The grouting was intended to reduce leakages from penstocks.

Robert Moses Niagara Power Plant

This project consists of an intake section, two parallel conduits about 6.4 km (4 mi) long, an open canal about 1,219.2 m (4,000 ft) long, a main generating plant, and a pump-generating plant (Power Authority of the State of New York, 1965).

Large quantities of rock excavation were required for construction of the intake, conduits, canal, and plants. At the start of the project different methods of establishing the breakline in rock were tried: line drilling on close centers, line drilling with light explosive charges placed at intervals in every second or third hole, slashing, and modified cushion blasting. However, none of those methods resulted in suitably clean walls for the placement of concrete. After considerable experimentation, presplitting (the establishment of a free surface or shear plane in the solid by the controlled usage of explosives and blasting accessories in appropriately aligned and spaced drill holes) was developed and superior results were obtained (Paine, Holmes, and Clark, 1961). Apparently this was among the first large scale application of presplitting.

More than 5,355,000 m^3 (7,000,000 yd^3) of excavation, mostly rock from the Lockport through the Queenston formations were removed to accommodate the massive power plant (Fig. 9). Another ~1,912,500 m^3 (2,500,000 yd^3) were removed for the forebay.

Feld (1966) reported that rock movement from load release occurred during the excavation for the two parallel conduits. The trenches in rock were up to 50.3 m (165 ft) in depth. According to Feld with the excavation to subgrade, the sides at 11.6 m (38 ft) above subgrade moved inward 1.3 cm (1/2 in) and the subgrade developed a longitudinal crack and about a 7.6 cm (3 in) heave at the center of the trench. One month later the heave had increased to 21.6 cm (8-1/2 in) at the center and was 6.4 cm (2-1/2 in) at each side wall. Those movements were accompanied by loosening of the exposed rock sheets at subgrade and with ravelling of the rock at the side walls. With the completion of the concrete conduits, backfilling, and filling the conduits, apparently normal stable conditions were restored. The concrete conduits were designed with articulated arch roofs and longitudinal center joint in the floor to provide flexibility should internal rock movements occur.

FUTURE OF THE FALLS

In his "Principles of Geology," Lyell (1860, p. 181) suggested that on the basis of contemporary rates of recession, the Falls would eventually reach Lake Erie in $\sim$30,000 yr. Projections of the twentieth century rate of $\sim$2 ft yr^{-1} (0.6 m yr^{-1}) via the shortest (west or Chippewa) channel (Frontispiece II and Fig. 10) yields 48,000 yr for the 29 km (18 mi) distance. Such projections are based on fallacious assumptions but the results may be as good as any number that could be generated considering the complicated scenario of retreat (Philbrick, 1974). Philbrick (1974) suggests the following sequence of events during progressive recession of the Falls and Gorge to Lake Erie (see Fig. 10):

(1) Retreat at 2 ft yr^{-1} (0.6 m yr^{-1}) causes capture of the American channel above Goat Island about 2000 yr AP and within 7000 yr AP, a lowering of the Chippewa-Grass Island Pool above the Falls with consequent slight lowering of Lake Erie levels.

(2) Splitting of the Horseshoe Falls into first, two falls, then three, and subsequently two falls again as recession causes the channel to split at Navy Island and again around the north end of Grand Island.

(3) Headward migration of Chippewa Horseshoe Falls down south dip of the Lockport Formation to a height of 50 ft (15 m) at which point recession is so retarded as to make it a quasi-stationary waterfall (similar to present American Falls).

(4) Rapid erosion to form a broad, gentle gorge and stepped rapids in the Salina Group rocks. Eventual capture of slower-eroding Tonawanda (east) Channel by Chippewa Channel near upstream end of Grand Island.

(5) Marked slowing of recession to Lake Erie and Niagara River mouth as gorge develops in Bertie dolomite and single Falls on overlying tough Onondaga Limestone.

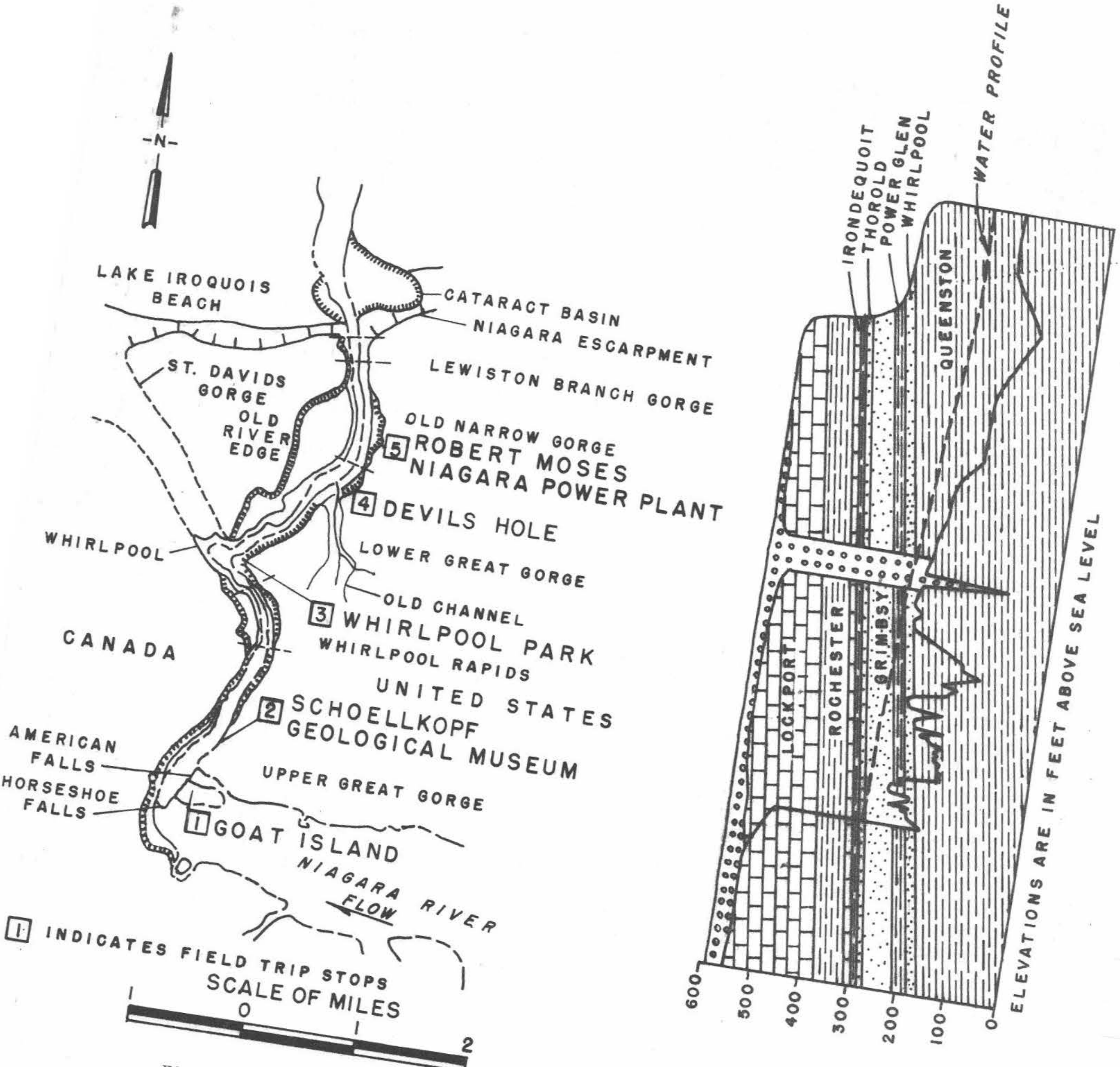

Figure 1. Location map of the Niagara Gorge showing field trip stops, Gorge sections (see Table 1), and profile modified from American Falls International Board (1974).

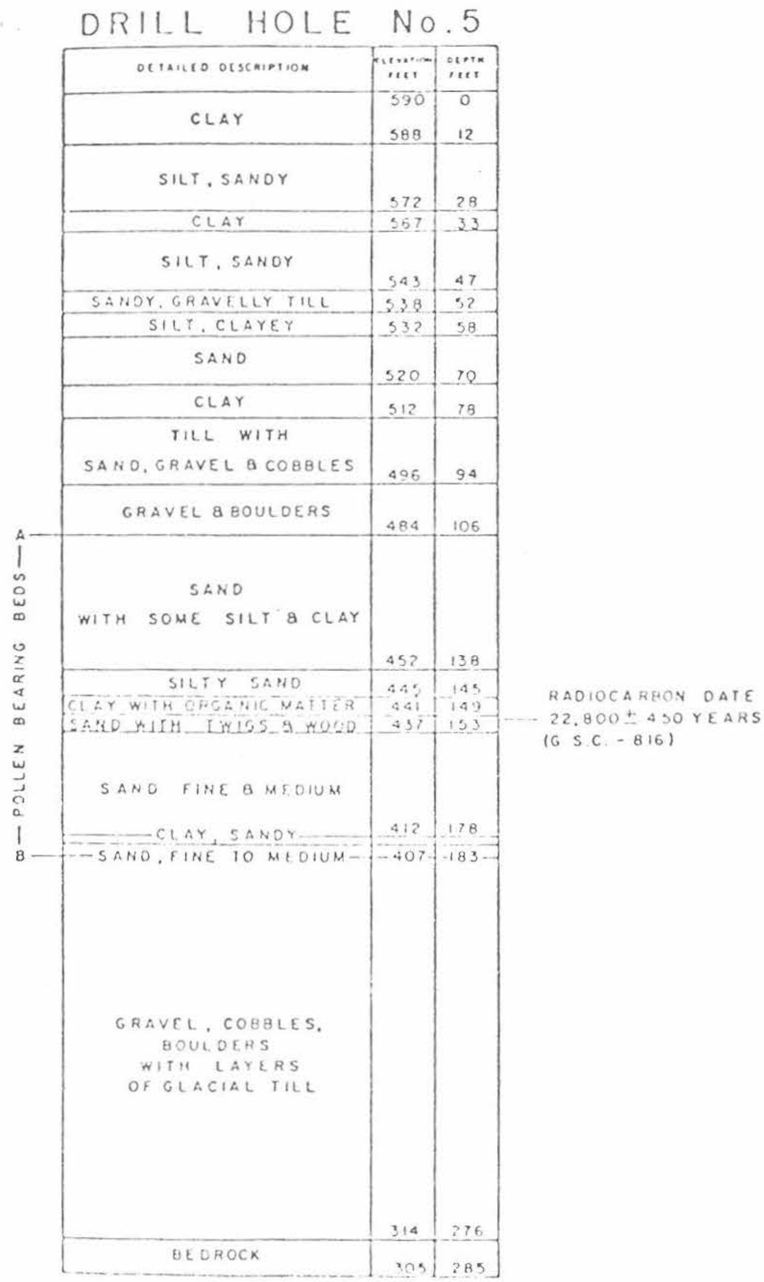

Figure 2. Generalized drill log no. 5 from the upper end of St. Davids Gorge. The radiocarbon date may provide a maximum age for advance of Late Wisconsin ice across the area. The organic matter is assumed to be Middle Wisconsin based on this date and the pollen assemblage; the lower tills may be Middle and/or Early Wisconsin (or older).

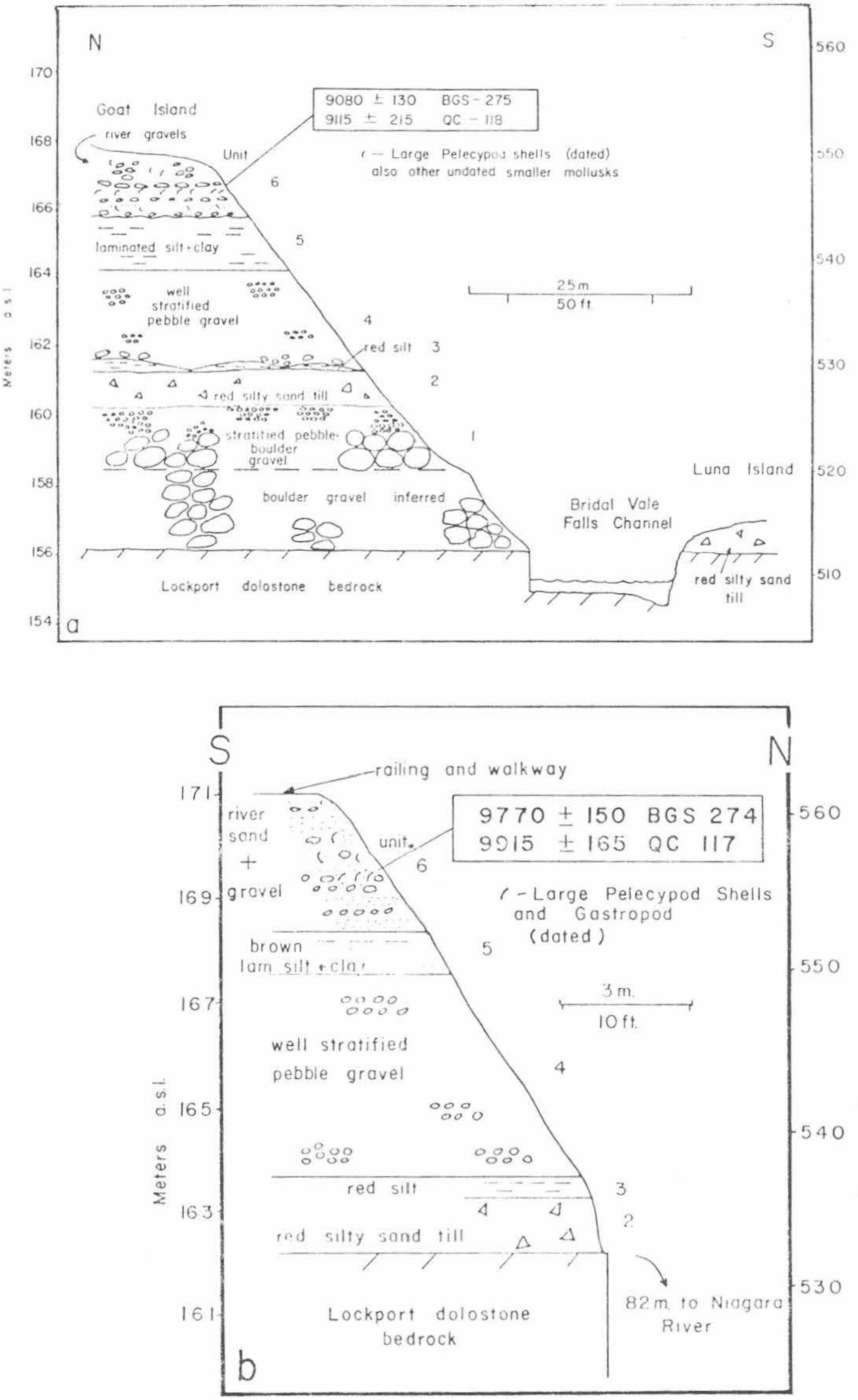

Figure 3. Stratigraphic sections through the surficial deposits at Goat Island (3a) and Whirlpool Park (3b). From Calkin and Brett (1978).

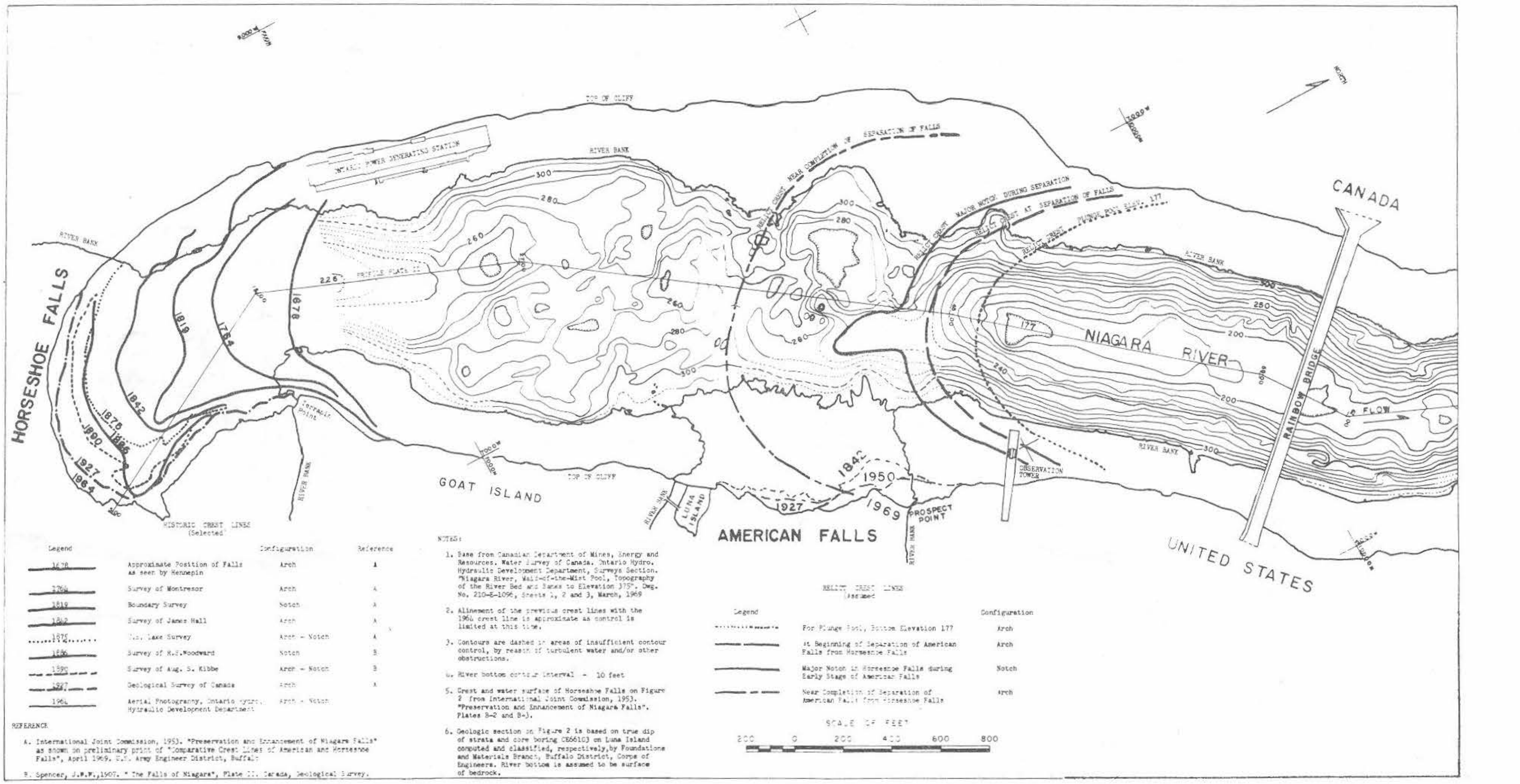

Figure 4. Former crestlines of the American and Horseshoe Falls. Modified after Philbrick (1970, Figure 1); former crestlines at the American Falls added from American Falls International Board (1974, Plate C29).

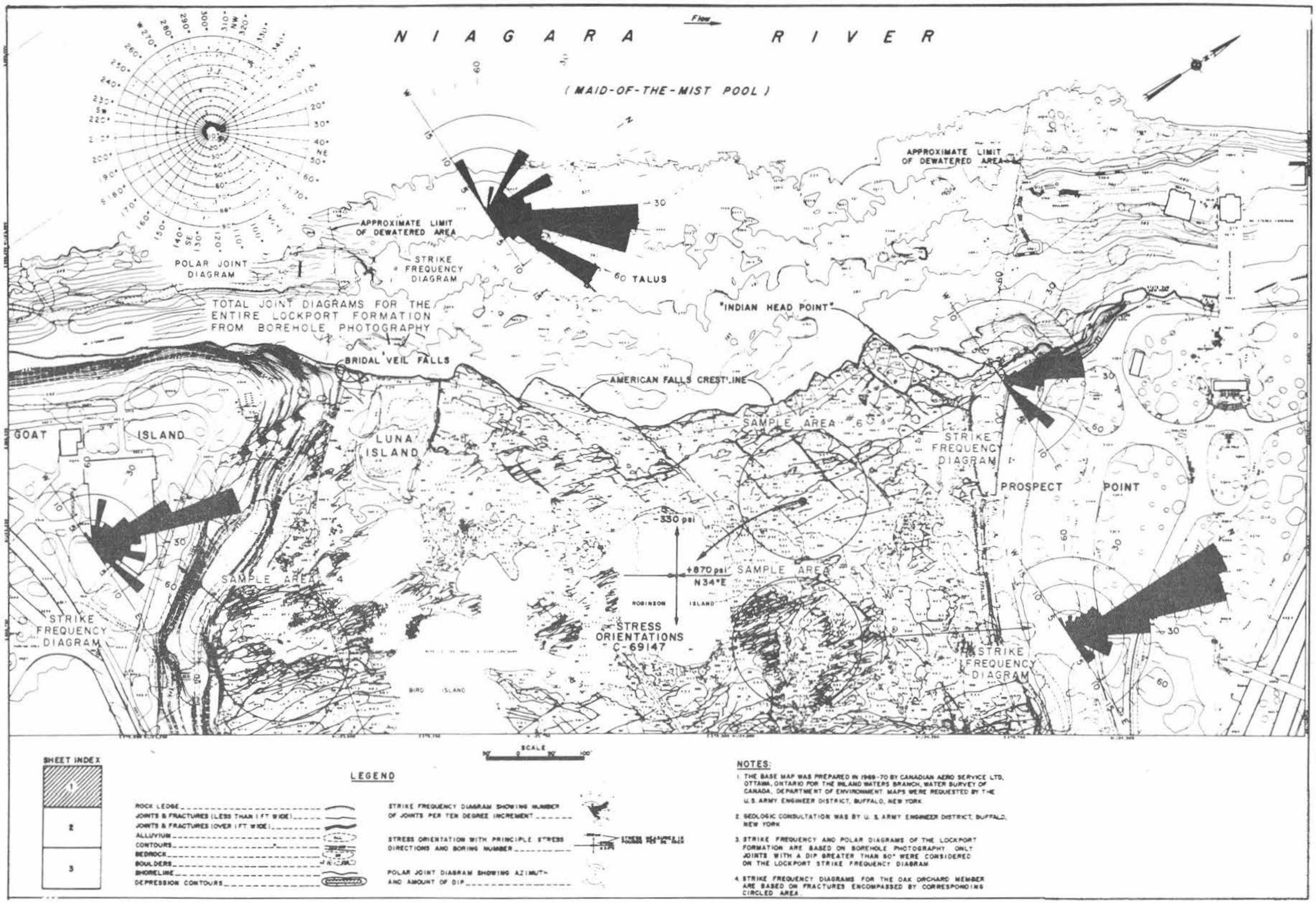

Figure 5. Joints in Lockport Formation of dewatered river bed. From American Falls International Board (1974, Plate C11).

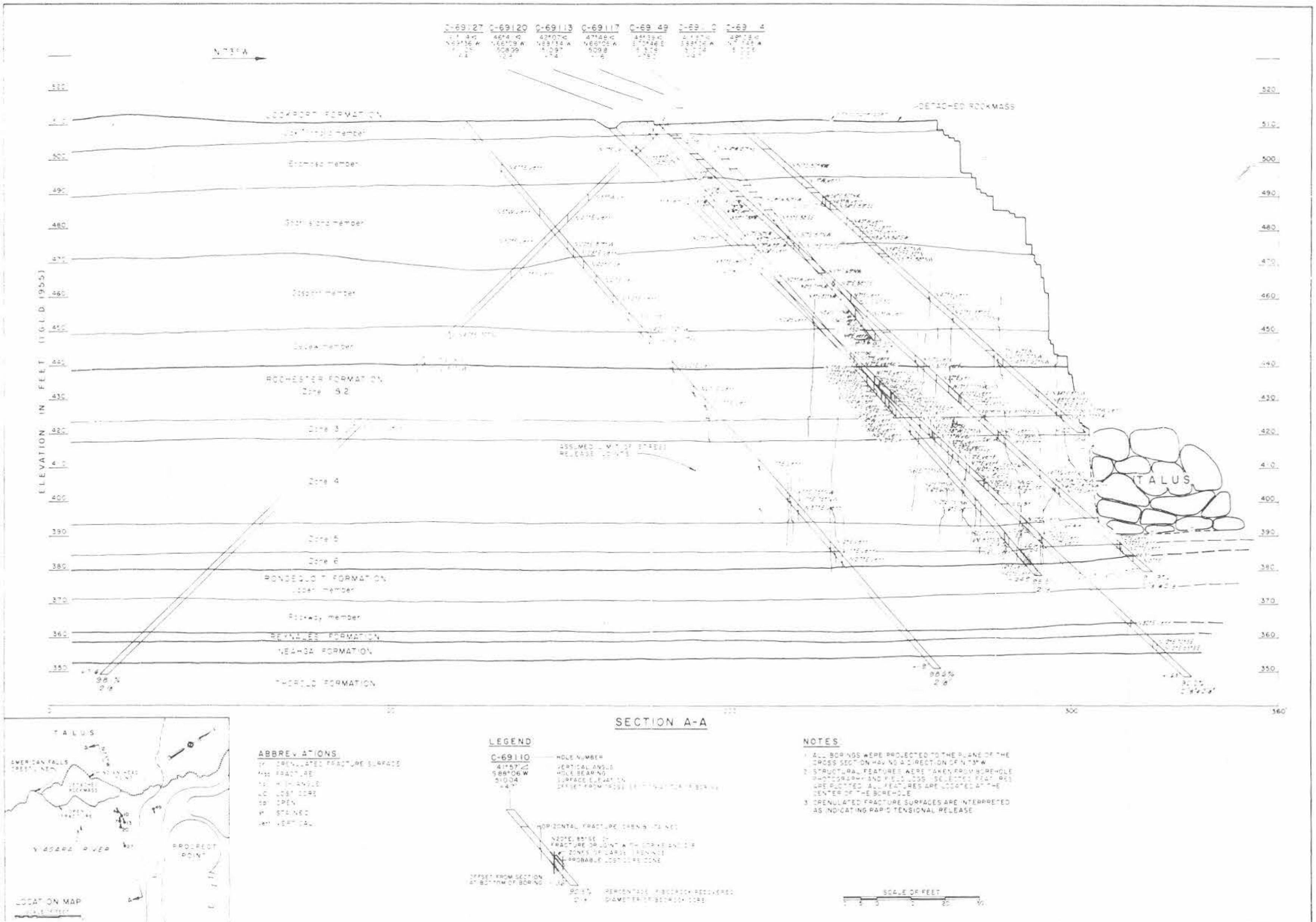

Figure 6. Geologic cross section, Prospect Point flank. From American Falls International Board (1974, Plate C16).

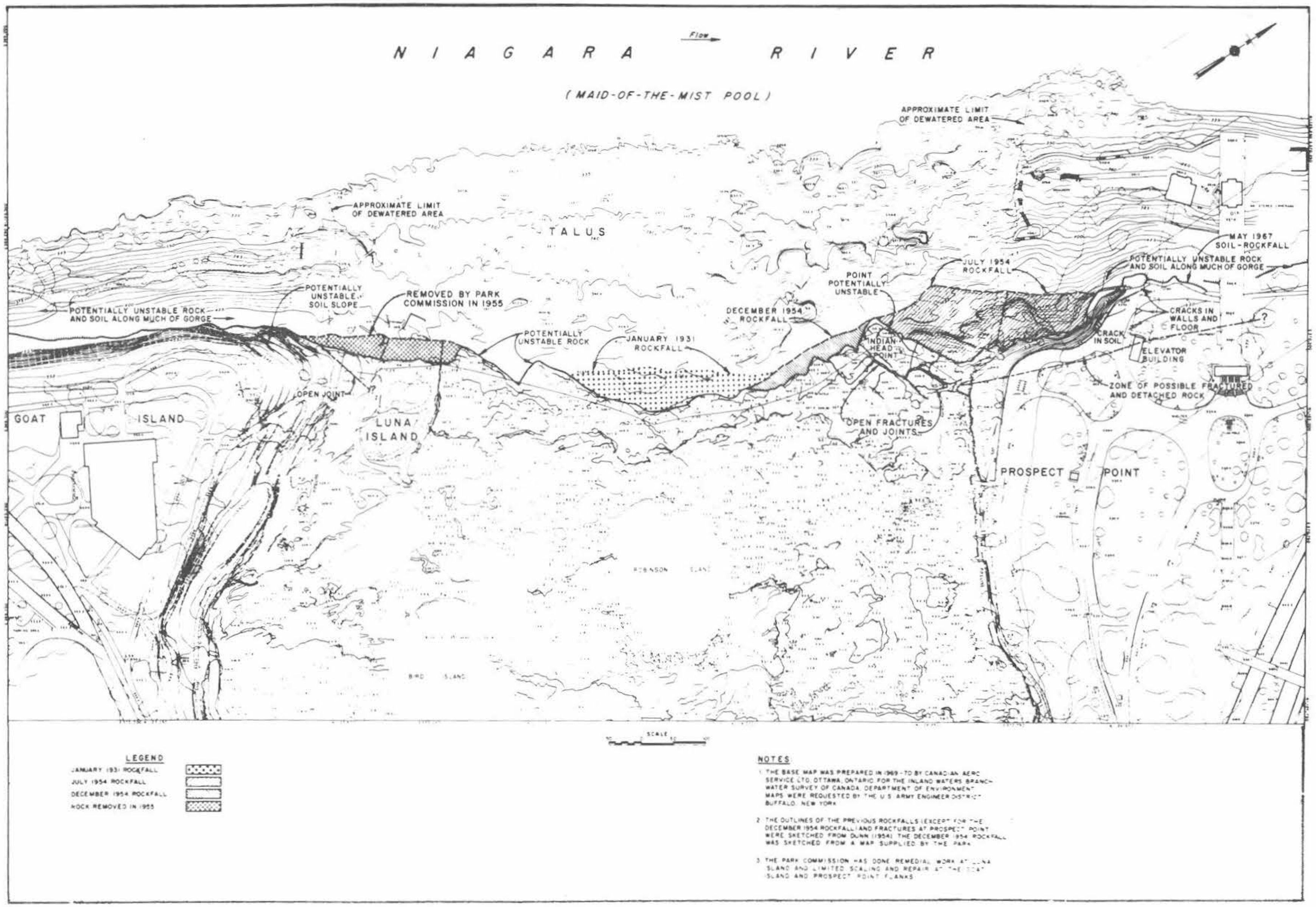

Figure 7. Rockfalls and unstable areas along American Falls crest and flanks. From American Falls International Board (1974, Plate C30).

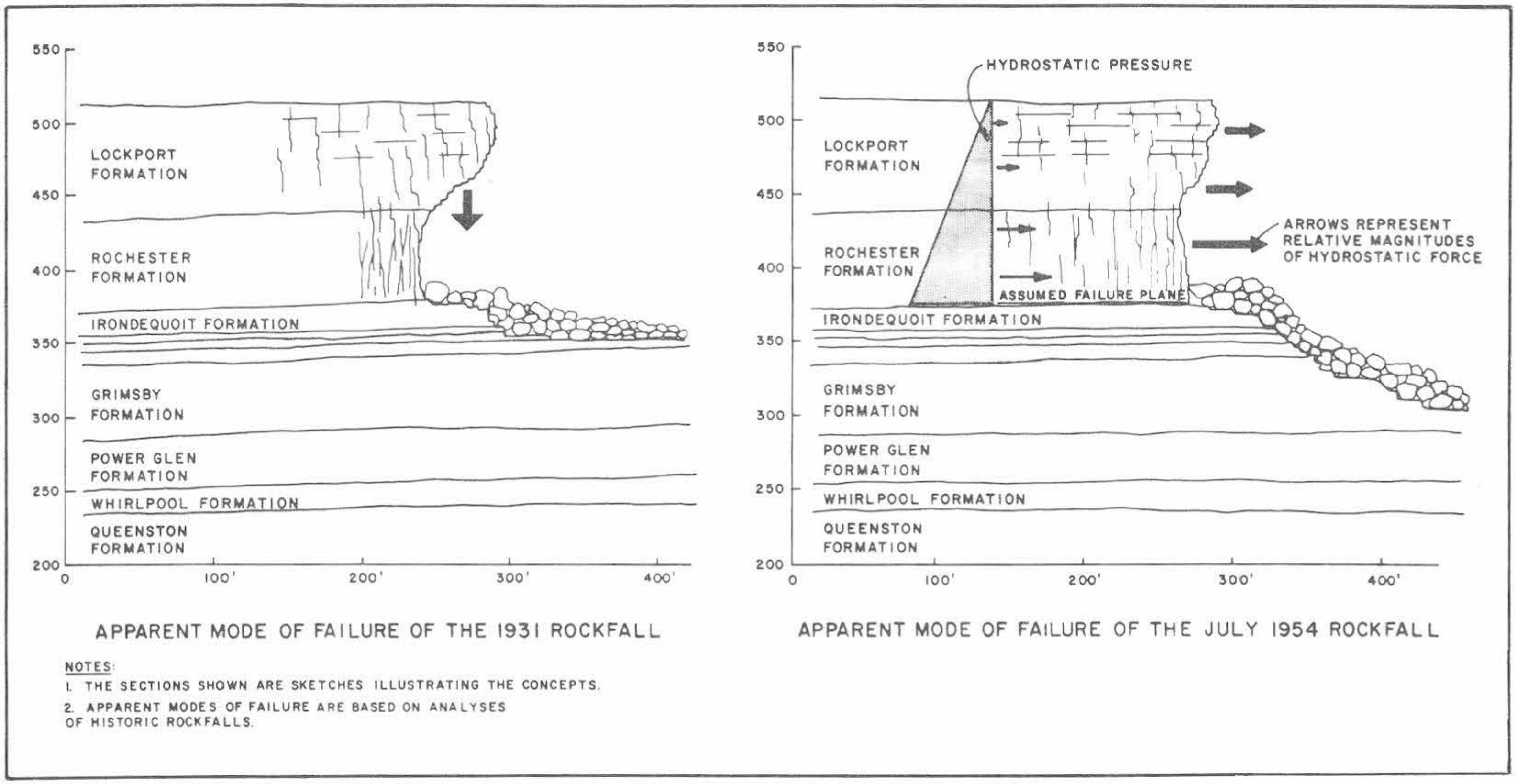

Figure 8. Modes of failure, American Falls. From American Falls International Board (1974, Plate C45).

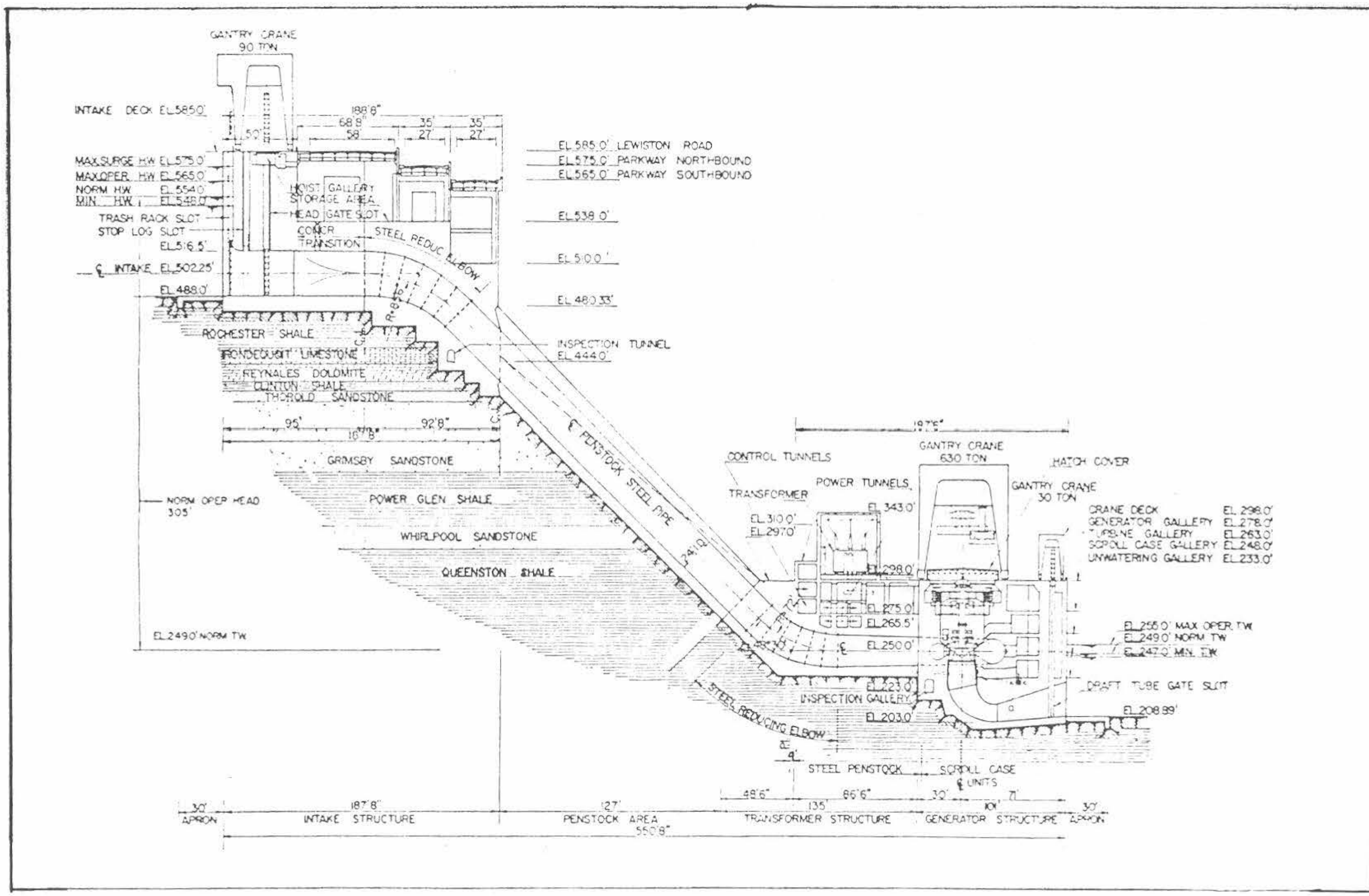

Figure 9. Cross section, Robert Moses Niagara Power Plant. From Power Authority of the State of New York (1965, p. 24).

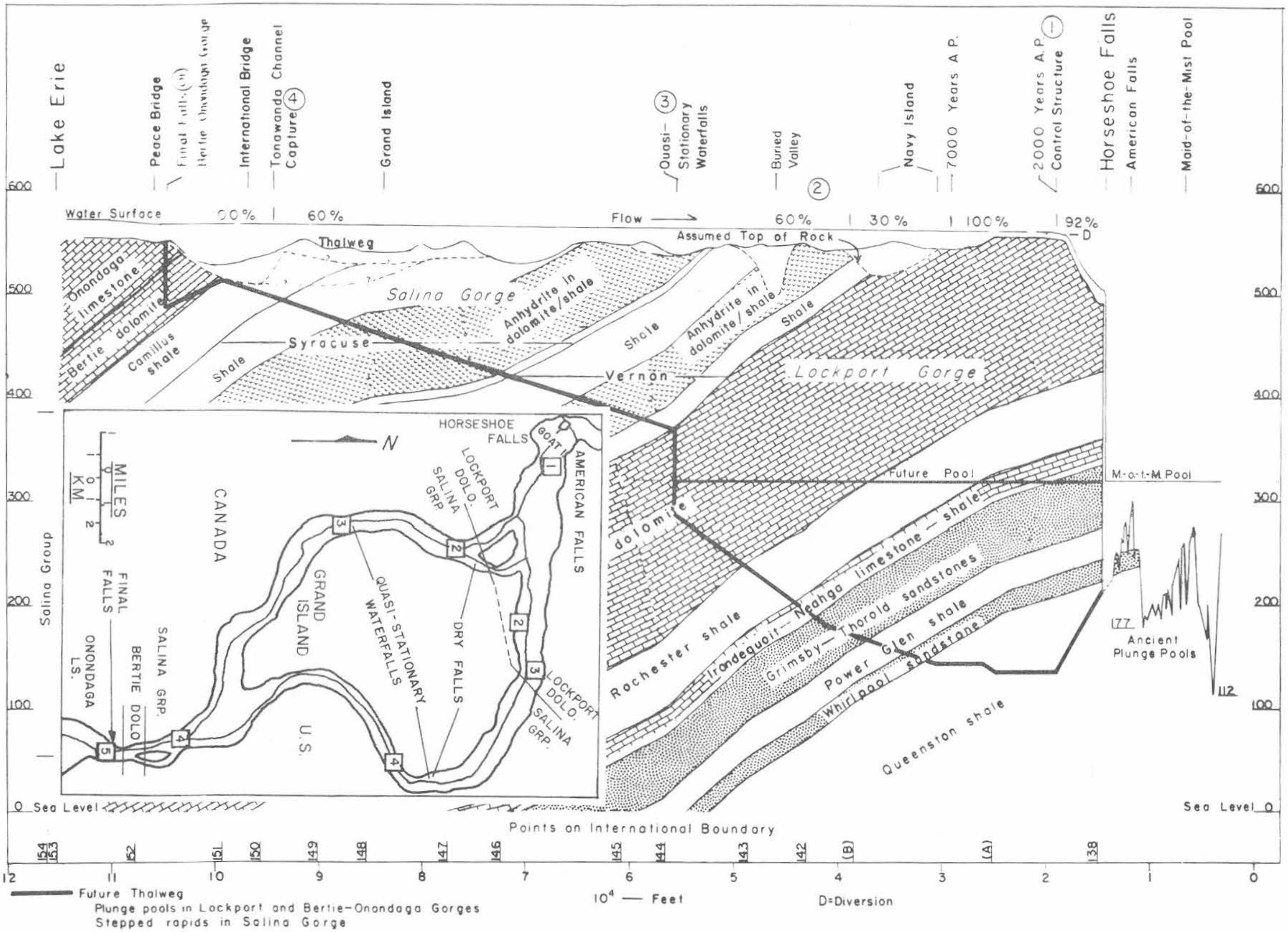

Figure 10. Geologic cross section along the thalweg of the Chippewa Channel (west branch) Niagara River, Lake Erie to Horseshoe Falls. Numbers on top of profile correspond to those on inset map (with equivalent numbers having equivalent dates on both channels) and events in text. Percentages refer to the share of undiverted flow carried during recession of the Falls through the Chippewa Channel. Modified from Philbrick (1974).

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ROAD LOG AND STOP DESCRIPTIONS FOR GLACIAL AND ENGINEERING GEOLOGY ASPECTS OF THE NIAGARA FALLS AND GORGE

(Route to Goat Island duplicates that of Drexhage and Calkin (1982, this volume, Fig. 1). Route and stops along the Gorge are shown in Fig. 1. Figure 11 shows the Lewiston - Lockport Spillway Stop 6 to Marriott Inn route.)

CUMULATIVE MILEAGE	MILES FROM LAST POINT	
0.0	0.0	From Buffalo Marriott Inn turn right at signal light onto Millersport Hwy. and immediately right onto Youngman Expressway (I-290) west (Fig. 11).

		Travel over glacial Lake Warren plain with red clay colored by Queenston Shale. We are also at south margin of Lake Tonawanda plain.
6.0	6.0	Exit right to Rt. I-190 N to Niagara Falls.
7.3	1.3	Toll barrier, South Grand Island Bridge. Cross Tonawanda (east) Channel of Niagara River onto Grand Island.
		Subdued topography due to subaqueous deposition in Lake Warren and washing by initial stages of Niagara River System.
10.7	3.4	Crest of Niagara Falls Moraine.
13.0	2.3	North Grand Island Bridge across Tonawanda Channel of the Niagara. Note spray of Falls at Left.
14.0	1.0	Exit right off I-190 to Robert Moses Parkway to Falls. Niagara Falls Water Treatment Plant and Hooker Chemical Plant on right west of bridge.
15.4	1.4	Structures at left house gates for water intakes to Robert Moses Niagara Power Plant.
		Pass Carborundum Company and Niagara Falls Sewage Treatment Plant on right, Grass Island Pool and control structure (mostly on Canadian side) on distant left.
18.0	2.6	Road bears right under Goat Island Bridge to stop sign.
18.4	0.4	Turn right onto Falls Street and right again onto Rainbow Blvd.
18.7	0.3	Turn right onto First St; proceed through intersection at light over bridge and American Rapids onto Goat Island. Circle island past Horseshoe Rapids.
19.2	0.5	Turn into parking lot after passing Terrapin Point.

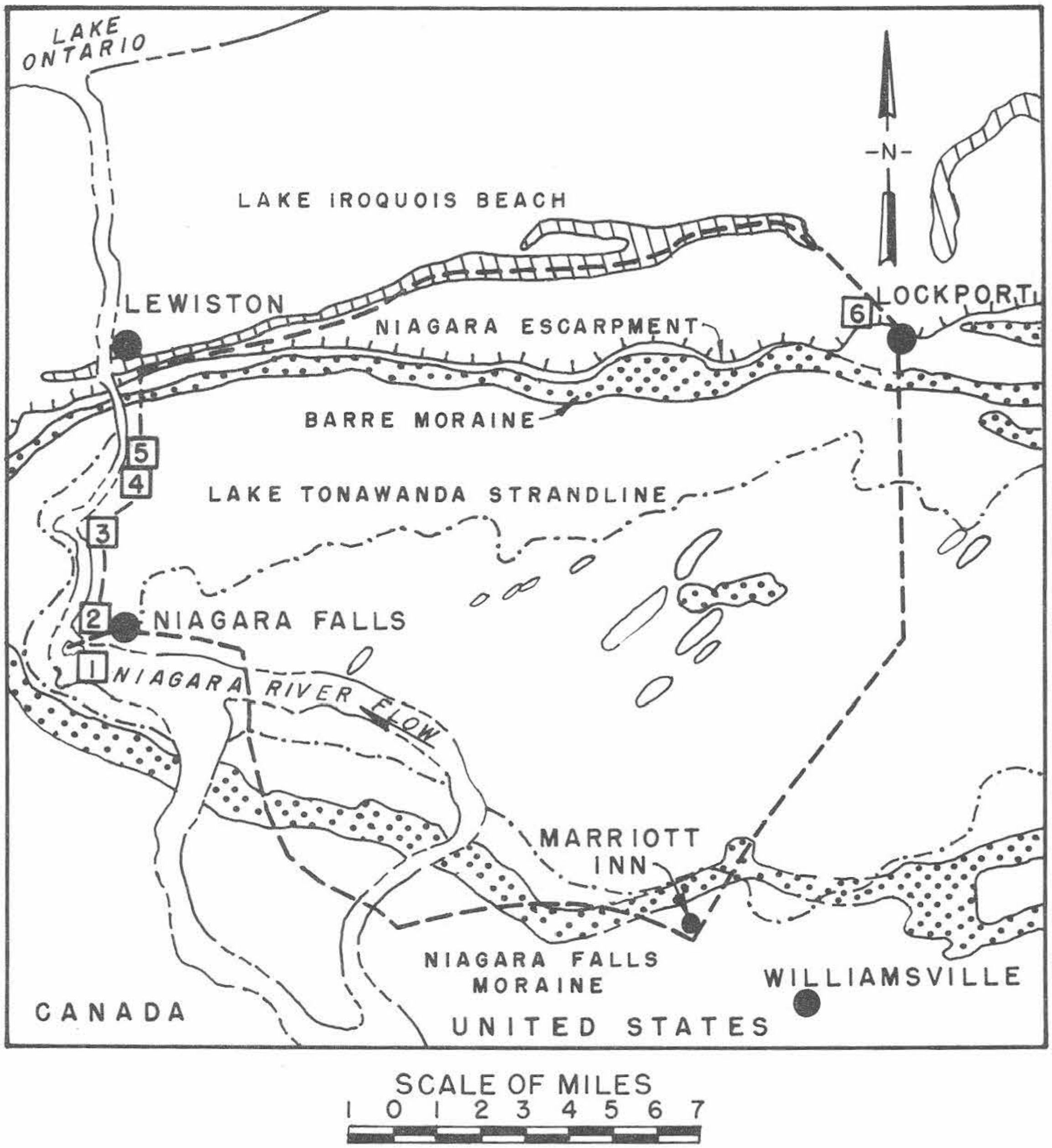

Figure 11. Map of field trip route. Base modified after Muller (1977b).

STOP 1. GOAT ISLAND

The Horseshoe Falls is seen between emerged bedrock terraces of the ancestral river. The Niagara Falls Moraine forms the bluff behind the Falls on the Canadian side. The bedrock slopes which form the Horseshoe and American Rapids are connected beneath Goat Island, at this site, and represent the eastern bank of Spencer's (1907) "pre-glacial Falls-Chippewa Valley." This was believed to trend southward from headwater ~2 Km (1.2 mi) to the north (near head of north-trending St. Davids Gorge). Figure 3a shows the surficial deposits on Goat Island.

The stratigraphy, structure, talus accumulation, and general location of previous rockfalls at the American Falls will be observed at this stop.

Leave parking lot and take exit back to bridge.

20.5	1.3	Leave Goat Island across bridge over American Rapids; proceed straight past Hotel Niagara along First St. (4 lights) to intersection with Main St.
21.2	0.7	Turn left onto Main St. and immediately take first right following signs to Schoellkopf Geological Museum.
22.7	1.5	Park at Museum.

STOP 2. SCHOELLKOPF GEOLOGICAL MUSEUM

This is the site of the massive rockfall that destroyed the Schoellkopf Powerhouse Stations 3B and 3C and damaged 3A on June 7, 1956. This area of failure will be observed and described.

Leave Museum and retrace route back to Main St.

23.0	0.3	Turn left on Main St.
23.1	0.1	Turn left immediately at light onto Robert Moses Parkway to Whirlpool.
25.4	2.3	Turn left and immediately right around traffic oval into Whirlpool State Park.

STOP 3. WHIRLPOOL PARK

Descend from the parking lot a series of bedrock or gravel river terraces to Gorge margin and view of Whirlpool. The Whirlpool formed soon after 9800 yr BP when the retreating Falls intersected the buried St. Davids Gorge (see Figs. 1, 2, 3b). Known since the time of James

Holland and Charles Lyell, this gorge is as deep and nearly as wide as the Upper Great Gorge (Hobson and Terasmae, 1969), and extends northward across the Escarpment at the community of St. Davids, Ontario, to the mouth of the Niagara at Niagara-On-The-Lake. Taylor (1933) showed that it probably reached as far south (upstream) as the Railroad Bridge where till was encountered in the Gorge bottom and probably up to the head of the Whirlpool Rapids section (Fig. 1). The age and nature of the drift fill (Fig. 2) suggest cutting occurred during or more probably before Middle Wisconsin time under nonglacial conditions when river discharges and baselevel conditions were similar to those of the present.

The Gorge walls expose Lockport Dolostone down through Lower Silurian, Whirlpool Sandstone (type area).

Leave Whirlpool with right and immediate left turns half around traffic oval to Parkway going north.

27.2	1.8	Turn right (at first opportunity) into Devils Hole parking lot.

STOP 4. DEVILS HOLE

This is a plunge pool formed by drainage from Lake Tonawanda via a shallow channel east of the main Niagara channel (Fig. 1). The cave has enlarged through solution localized along a master joint. This site is a good one for viewing the stratigraphy and structure of the Lockport Formation.

Bloody Run, the stream now occupying the lower end of this channel, is named after an Indian massacre of settlers which is reported to have occurred here in 1763.

Leave Devils Hole parking onto Rt. 104 heading north. Pass Niagara University on right and nearby Hyde Park Landfill site of Hooker Corporation.

27.9	0.7	Turn right into parking area for public Power Vista of Robert Moses Niagara Power Plant.

STOP 5. ROBERT MOSES NIAGARA POWER PLANT

A brief stop at this plant will be made to observe the limited exposures of rock excavation surface. The Power Vista itself displays models of Niagara Falls and Gorge, the power generating plant setup and in addition, views of the Gorge stratigraphy. Elevator service to the base of the Power Plant Access Road (traversing good exposures of the Queenston through the Lockport formations) may be obtained for geology field trips with special permission.

Leave Power Vista road right (north) onto Rt. 104E.

29.5	1.6	Cross Barre Moraine at crest of Niagara Escarpment with view of Lake Iroquois plain to north.
		Descend Escarpment; note meandering Lower Niagara River with drop of less than 1 m in 6 mi (9 Km) distance to Lake Ontario.
30.5	1.0	Turn right (east) of underpass following Rt. 104 E (Ridge Rd.) with left turn at stop sign.
		Rt. 104 E here follows crest of wave-cut bluff of Lake Iroquois with thin lacustrine silts on till. Niagara Escarpment at right.
35.7	5.2	At Dickerson Rd., Rt. 104 starts to follow crest of Lake Iroquois beach ridge.
41.3	5.6	Cross Rt. 425 (Cambria Rd.). A second ridge occurs to North (North Ridge spit) probably derived from the Lockport spillway to the east.
45.1	3.8	Turn off Rt. 104 onto Rt.93 at fork and proceed straight (not on Rt. 93) onto Stone Rd.
48.1	3.0	Turn right after crossing Eighteenmile Creek onto Plank (= Purdy) Rd. Enter bedrock embayment of Lockport spillway system for Lake Tonawanda.
48.8	0.7	Turn left up Escarpment on East Jackson St. The Lockport Wastewater Treatment Plant on right is Lockport Gulf site of Calkin and Brett (1978) and Miller and Morgan (1982). Subsurface exposure of the Lockport Gulf site have revealed the following stratigraphy:

Top 0.5 Fill

2.5 m Massive silty clay (post glacial)

2.0 Gray organic silt, clay, and marl with pollen dominated by spruce; basal wood date of 10,920± 160 yr BP (I-5841)

3.5 Laminated red and gray sand, silt, and clay (Lake Iroquois?)
Base 9.0 Red clayey sand and gravel interpreted to be till (only in borings).

East Jackson St. follows one of the three major spillway channels at Lockport.

49.4	0.6	Turn back, sharp right onto Glenwood Ave. past St. Patrick's Cem. Kame deposits are related to Albion-Rochester Moraine.
49.7	0.3	Turn left onto North Transit Street up escarpment.
49.8	0.1	Turn right at top onto Outwater Drive.
50.3	0.5	Turn right into short loop road to escarpment edge just before reaching water tank.

STOP 6. OUTWATER PARK, LOCKPORT

View northward from Lockport Escarpment of Lake Iroquois plain and Lake Ontario (if clear) 11 mi. distant. The Lockport Gulf (W. Jackson St.) spillway circles just below. Good exposures of the bedrock surface and northeast-southwest oriented striations occur in the park dump area to the west of the water tank.

50.4	0.1	Turn left back eastward on Outwater Drive.
51.0	0.6	Turn right (south) onto North Transit.
51.7	0.7	Cross Erie/New York State Barge Canal proceeding south on Transit Road (Route 78).
51.9	0.2	Cross High Street on crest of Barre Moraine ridge.
52.6	0.7	Cross Summit Street at light, another of four Barre Moraine ridges mapped by Gilbert (Kindle and Taylor, 1913).
57.5	4.9	Cross Tonawanda Creek and bear right onto Route 263 South (Millersport Highway). You are in middle of the former River-Lake Tonawanda plain. A few low NE-SW-oriented drumlins can be seen to the northeast.
66.2	8.7	Turn right at light into Buffalo Marriott Inn.