LATE PLEISTOCENE MELTWATER DRAINAGE THROUGH CENTRAL NEW YORK

Bryce M. Hand
Department of Geology, Syracuse University

Introduction

When the retreating margin of Wisconsinan ice last stood in central New York, large quantities of meltwater poured eastward across uplands separating north-south valleys occupied by finger lakes. In some places, these ancient meltwater routes are inconspicuous; more commonly, they are impressive gorges produced by vertical incision or waterfall migration. On this trip we will examine channels, waterfalls, dry finger lakes, and remnants of deltas produced during this phase of deglaciation.

The importance of meltwater in the deglacial history of central New York has been recognized for many years. Fairchild (1909; 1932) mapped channel complexes from Batavia to Oneida, relating them to discharge from proglacial lakes north of the Valley Heads moraine (which today dams the southern ends of Seneca, Cayuga, and other Finger Lakes), and to "Great Lakes" flow from the Lake Erie basin and beyond. Sissons (1960) described meltwater scour features and sedimentary deposits between Syracuse and Oneida, and demonstrated that englacial, subglacial, and supraglacial flow were locally important. (These types of flow undoubtedly occurred in our area, but ice-marginal drainage was paramount.) Krall (1966) studied fluvioglacial drainage features in the region between Skaneateles and Syracuse. Other discussions bearing on the Syracuse channels have appeared in guidebooks of the New York State Geological Association (Muller, 1964; Grasso, 1970; Hand and Muller, 1972; Hand, 1978).

Despite the remarkable record of meltwater events displayed in central New York, complete historical reconstruction may never be possible. Lack of continuity is a problem; channels traversing upland regions are interrupted by north-south "through" valleys that held lakes (or ice) when the channels were active. Moreover, many erosional features are products of multiple episodes of ice advance and retreat, each accompanied by meltwater drainage that may or may not have been similar to drainage during other episodes. Constructional features (deltas) are temporally more coherent, in that they all must be products of the final phase of ice withdrawal. However, as drainage patterns evolved in response to changing lake levels or the opening of new escape routes, deltas have been destroyed or modified to the point where their significance is not always clear. Finally, the ever-changing configuration of the ice margin (which often provided one bank for the meltwater stream) is not well constrained.

The point of this trip is to observe a Whitman's Sampler of the types of evidence that remain. Hopefully, ambiguities generated by the inadequate record will be compensated by the fun of weighing alternatives and identifying fatal flaws in our colleagues' (and your leader's) interpretations.

Regional Setting

The features we will see are located along the northern margin of the Appalachian (Allegheny) Plateau, which rises southward from Syracuse and is bordered on the north by the Ontario Lowland. Ancient north-south valleys within the Plateau provided favorably oriented avenues for Pleistocene ice tongues in advance of the main glacier front. These north-south valleys became widened and deepened, and modified into the U-shaped troughs that today are termed "through" valleys. Otisco, Onondaga and Butternut valleys are examples, as are the valleys occupied by finger lakes, farther west.

During a pause in ice retreat (Port Bruce Stade), the Valley Heads moraine developed as a massive drift barrier plugging these many "through" valleys. ("Valley Heads" derives from the fact that the moraine now serves as a drainage divide between northward and southward drainage in trough-like valleys that otherwise are through-going.) Ice withdrawal from the Valley Heads position created local "finger" lakes that initially drained southward, over the moraine and into the Susquehanna basin. In time, these lakes developed communication with their siblings to the east or west through spillways or open water.

As the ice continued to recede from the Appalachian plateau's northward-sloping margin, eastward drainage became possible and the lakes' southward outlets were abandoned. During much of this time, Great Lakes water from the Erie and Huron basins (Lake Warren) augmented meltwater from across central and western New York to provide discharge that must have been comparable to that of the Niagara or St. Lawrence today. As these torrents spilled eastward from one "finger" lake to the next, they created the spectacular channels and deltas that we will examine today.

References

Fairchild, H.L., 1909, Glacial waters in central New York: New York State Museum Bull. 127, 66 p.

Fairchild, H.L., 1932, Closing stage of New York glacial history: Geol. Soc. Amer. Bull., v. 43, p. 627-662.

Grasso, T.X., 1970, Proglacial lake sequence in the Tully Valley, Onondaga County: New York State Geol. Assoc. 42nd Ann. Meeting, Guidebook, p. J1-J23.

Hand, B.M., 1978, Syracuse meltwater channels: New York State Geol. Assoc. 50th Ann. Meeting, Guidebook, p. 286-314.

Hand, B.M., and Muller, E.H., 1972, Syracuse channels: evidence of a catastrophic flood: New York State Geol. Assoc. 44th Ann. Meeting, Guidebook, p. I1-I12.

Krall, D.B., 1966, Fluvioglacial drainage between Skaneateles and Syracuse, N.Y.: unpubl. M.S. thesis, Syracuse University, 158 p.

Muller, E.H., 1964, Surficial geology of the Syracuse field area: New York State Geol. Assoc. 36th Ann. Meeting, Guidebook, p. 25-35.

Sissons, J.B., 1960, Subglacial, marginal, and other glacial drainage in the Syracuse-Oneida area, New York: Geol. Soc. Amer. Bull., v. 71, p. 1575-1588.

ROAD LOG

USGS 7 1/2 minute topographic quadrangles relevant to this field trip:

OTISCO VALLEY
MARCELLUS
SOUTH ONONDAGA
JAMESVILLE
SYRACUSE WEST
SYRACUSE EAST

Cumulative Miles	Interval Miles	Route Description
		■ From Hamilton, north on NY 12B to US 20. West on US 20 to I-81 at LaFayette.
		Route crosses Cowaselon, Chittenango, Limestone and Butternut Valleys, and intervening upland spurs.
		Field trip mileage log begins at

LaFayette (US 20) interchange with I-81 (Interchange #15).

0.0	0.0	■ Left, entering I-81 southbound.
2.5	2.5	■ Right, into Rest Area. **STOP 1**.

View across Tully valley segment of Onondaga valley. This is the southward-directed "stem" of the Y-shaped trough ("through valley") system that will be the focus of this trip; Cedarvale trough can be seen extending northwestward from the three-way junction, but the northeastward continuation of Onondaga valley (toward Syracuse) is not visible from here.

As Wisconsinan ice retreated from the Valley Heads moraine (Tully moraine segment, four miles south of here), proglacial Lake Cardiff was impounded between the moraine and the receding ice front. Initial drainage was southward across the Tully moraine (1200') to the Susquehanna River. Later escape was westward (through Joshua and Navarino Channels) into adjacent lakes controlled by slightly lower segments of Valley Heads moraine.

The focus of this trip, however, will be on still later phases of drainage, corresponding to ice-front positions within about 4 miles of downtown Syracuse (and lake levels below about 900'), when meltwater from as far west as Lake Huron poured through central New York. It was this flow that scoured the Split Rock channels, Pumpkin Hollow, "Syracuse" channels (the several outlets crossing the upland between Onondaga and Butternut valleys), and other prominent canyons across uplands farther east and west.

■ Continue south on I-81.

5.2	2.7	*View of Tully moraine.*
6.6	1.4	■ Exit I-81 at Tully (Interchange #14).
6.7	0.1	■ Left at "T" (end of off-ramp).
6.8	0.1	■ Right (W) on NY 80.

The road follows the crest of the Tully moraine. This is predominantly a kame moraine, composed chiefly of outwash. Irregular *topography is due to kettles and (to a lesser extent) channeling.*

9.2 | 2.4 | ■ Right on Woodmancy Road.

9.4 | 0.2 | ■ Hidden Falls Road. **STOP 2.**

Excellent view of the north (proximal) face of Tully moraine. This steep face, which was banked against the ice, contrasts with the gently sloping (kettled) topography south of the moraine crest. This is the plug that held a lake in Onondaga valley.

Crest of the moraine stands at 1200'; 2 miles north of here, the valley floor is 600' lower. Several hundred feet of unconsolidated valley fill (till, outwash, lake clays, and postglacial alluvium) occur even in the deeper parts of the valley.

Rounded gravels in the roadside exposures are typical of the kame materials making up the bulk of the moraine. Clasts of local bedrock predominate: Lower Devonian limestones and dolostones are especially abundant; brown siltstones from the Hamilton Group are somewhat underrepresented, because they are less durable. Somewhat farther-traveled are red Medina sandstone and white Potsdam(?) sandstone. Gneisses come from the Canadian shield.

■ Turn around and return to NY 80.

9.6 | 0.2 | ■ Right (NW) on NY 80.

17.8 | 8.2 | ■ Left (W) on US 20.

Shortly after turning onto US 20, observe delta remnants in Cedarvale trough. The flat tops of these remnants represent various lake levels.

21.0 | 3.2 | *Road descends into and crosses Navarino channel. The lake in Cedarvale/Onondaga valley discharged for a while through this channel, which held lake level at just over 1000'. To the southwest (downstream), Navarino channel terminates in a small delta on the east wall of Otisco valley.*

22.4 | 1.4 | ■ Right on Slate Hill Road.

25.9	3.5	■ Right (N) on NY 17.
26.1	0.2	■ Right, into Marcellus Town Dump. **<u>STOP 3</u>**.

This is the entrance to Pumpkin Hollow, easily the largest and most impressive meltwater cross channel in central New York. Carved in Marcellus (black) Shale, Pumpkin Hollow is over 300 ft deep, 500 to 1500 ft wide at the floor, and 3 mi long. It carried Great Lakes drainage from Otisco valley to the head of Cedarvale trough. (Virtually all of this flow had previously entered Otisco valley through Guppy Gulph.)

We have here clear evidence that retreat of Pleistocene ice from the Valley Heads position was interrupted by at least one brief readvance. Three miles north of Pumpkin Hollow begins a group of cross channels and scourways collectively called the "Split Rock series." Many of these scourways are one-sided, implying that the other bank was the ice itself, and that the axis of flow shifted laterally (northward) as the ice retreated. Like Pumpkin Hollow, the Split Rock series carried substantial throughput from farther west, probably including outflow from an early phase of Lake Warren.

The highest of the Split Rock series stands at about 900', whereas Pumpkin Hollow is excavated to 700'. Clearly, Pumpkin Hollow could not have been open when the Split Rock series was active, because drainage would simply have escaped via the lower (Pumpkin Hollow) route. Moreover, incision of Pumpkin Hollow <u>after ice had withdrawn far enough to permit development of the Split Rock series</u> requires <u>readvance to ≥900'</u> to initiate cutting of Pumpkin Hollow.

If, as suggested by Calkin and Muller (1992, pers. comm.), the Valley Heads moraine represents the Port Bruce Stade (≈14,000 Ka), the Split Rock series is reasonably assigned to ice retreat during the Mackinaw Interstade, and readvance (activating Pumpkin Hollow) to the Port Huron Stade (≈13 Ka).

It is not known how far the ice front retreated during the Mackinaw Interstade. It could well have cleared the northern margin of *the Appalachian Plateau, permitting an interval of "free drainage" (Erie channel?), as envisioned by Fairchild. The limit of Port Huron readvance is probably defined by the end moraine (eastern equivalent of Auburn/Geneva/Canandaigua moraines) about 2 mi south of Pumpkin Hollow.*

Although the Split Rock series is usually envisioned as the product of ice recession, it is probably equally valid to view it in the context of ice readvance. The flow is then seen as being pushed progressively southward and to higher elevations, until (somewhat above 900') it was either stopped or redirected to Pumpkin Hollow.

Disappearing Lake, in the west end of Pumpkin Hollow, occupies a shallow basin in the top of the Onondaga Limestone. If time permits, we may consider the origin of this depression and some of the lake's interesting behavior.

■ Return to NY 17.

26.3 0.2 ■ Right (N) on NY 17.

26.4 0.1 ■ Right (E) on Pleasant Valley Road.

Driving through Pumpkin Hollow. After about 2 mi, the valley suddenly widens as the north slope recedes. Krall (1966) has shown that Cedarvale trough once continued northwest (i.e., into the north wall of the valley), but became filled with till and was not subsequently reexcavated. A well along Seneca Tpk (NY 175) a mile northwest of here (el. 1030') penetrated 200+ ft of drift without encountering bedrock.

31.5 5.1 ■ Right (S) on Cedarvale Road.

31.7 0.2 ■ Left (SE) on Cedarvale Road. (Straight is Amber Road.)

33.6 1.9 ■ Left (E) on Tanner Road.

Road climbs onto remnants of deltas deposited by flow that entered the lake in Cedarvale trough after being discharged from Pumpkin Hollow. Delta sands and gravels are underlain by pink lake clays that can be seen here in the roadside ditch, the gully along old dirt road leading to gravel pit on right, and in a bank on left side of road.

34.6 1.0 ■ Right (S) on Makyes Road ("Onondaga Hill Road" on older maps).

Crossing delta surfaces at 720', 660', and 600'. All of these deposits relate to flow from Pumpkin Hollow. (Some higher levels, above 780', appear to be scoured till surfaces and small kame deltas from local drainage.) Early (high) deltas were eroded and their materials (in part) redistributed into lower deltas as the lake level fell. Note well preserved distributary channels.

35.6 1.0 ■ Right (W) on Cedarvale Road.

35.7 0.1 ■ Right (N) at Onondaga Fire Station.

35.8 0.1 ■ Enter W.F. Saunders & Sons' gravel pit. (PERMISSION REQUIRED.)

36.0 0.2 ■ W.F. Saunders & Sons' gravel pit. **STOP 4**.

Sand and gravel are being extracted from the Gilbert-style delta whose topset beds define the 720' and 780' levels. Angle-of-repose foresets dip down-valley (ESE) in a single spectacular set whose thickness reaches 70' or more.

Lake level for the 780' delta was probably controlled by the 770' threshold of the approach to Clark Reservation channel. The 720' delta probably formed after the lake outlet had shifted to the (700') threshold of Nottingham Road channel.

Delta deposits in Cedarvale trough must have formed during the final retreat of ice. Had they formed earlier, they would have been vulnerable to destruction or drastic alteration during subsequent ice advance. Also, it was not until final deglaciation that flow through Pumpkin Hollow became established (recall discussion at Stop 3).

The clast composition of these gravels (pebbles/cobbles of limestone, dolostone, red Medina sandstone, gneiss) indicates derivation overwhelmingly from glacial drift. Pumpkin Hollow, which provided the flow that built the delta, is cut in Marcellus (black) Shale, but there are few, if any, clasts of black shale in this pit. This suggests that Pumpkin Hollow *first formed in pre-Port Bruce time, became filled with drift during a subsequent glacial advance, and remained filled until final deglaciation (retreat from the Port Huron position). Excavation of the modern gorge would have begun with removal of this drift and its incorporation into the Cedarvale deltas.*

The alternative possibility, that pebbles of Marcellus Shale would not survive transport, is rejected because such clasts are very abundant in the extensive 620' delta deposits even farther from source. These shale-rich deposits prove that some deepening of Pumpkin Hollow occurred through bedrock erosion during deposition of the youngest (and lowest) deltas. Even the low delta gravels consist chiefly of "bright" (recycled drift) clasts, most of which were probably reworked from older deltas.

■ Return to Cedarvale Road.

36.3 0.3 ■ Left (E) on Cedarvale Road.

36.4 0.1 ■ Continue straight (E) on NY 80.

Driving on 620' delta terrace, which displays many well preserved distributary channels. The delta prograded southeastward, down Cedarvale trough to the 3-way junction of the "Y"-shaped valley system, then northeastward toward Syracuse. Further progradation into the Tully valley "stem" was impossible because Tully valley provided no exit for the water. In this direction, the delta terminates in a primary depositional front.

The outlet for the Onondaga Trough Lake at the time of the 620' delta is uncertain. Grasso (1970) assigned it to an intermediate level in the incision of Rock Cut channel (initial threshold ≈700; later lowered to 550'). Though I accept Rock Cut as the probable exit route, there seems no reason for a persistent "hang-up" near 600'. Indeed, the floor of Rock Cut seems to have been lowered suddenly from 700' to 550' (Hand and Muller, 1972). In light of this, I would suggest that Rock Cut and High Bridge channels were clear and over-deepened when the 620' deltas formed, and that tailwater control was established farther east by the 580' floor of Pools Brook channel or by the prevailing level of

Lake Iroquois into which Pools Brook channel emptied.

38.4 2.0 ■ Right (E) on unnamed road, immediately after entering Onondaga Nation Territory.

39.3 0.9 ■ Left (N) at "Stop" sign in Indian Village.

41.7 2.4 ■ Left (N) on NY 11.

42.1 0.4 ■ Right (E) on Rockwell Road, which becomes Sentinel Heights Road.

43.1 1.0 ■ Left (N) on Graham Road (first left after crossing I-81).

View of northern part of Onondaga valley. Gravel operation on far side of valley is in the lowest (520') terrace. Escape of water at this time must have been directly controlled by the level of Lake Iroquois, possibly by way of Erie channel (<410').

43.8 0.7 ■ Left (N) on LaFayette Road.

44.0 0.2 *Crossing western (inlet) end of Smoky Hollow. This is the southernmost of the "Syracuse" channels cut into the upland between Onondaga valley and Butternut valley. Smoky Hollow is excavated in Marcellus Shale. Incision began at 900'. The channel floor was at 790' at time of abandonment. Hence, while Smoky Hollow was its outlet, the lake in Onondaga valley at this point varied in depth from about 480' to 370'.*

45.3 1.3 ■ Right (S, becoming E) on NY 173 (Seneca Tpk).

47.2 0.9 ■ Left into Clark Reservation State Park.

47.4 0.2 ■ Parking lot in Clark Reservation State Park. **LUNCH and STOP 5**.

The abandoned waterfall at the head of Clark Reservation channel illustrates an efficient and characteristic mode of cutting through the Onondaga Limestone: by headward migration of a waterfall. (Channels in the Marcellus Shale more likely were created by vertical downcutting, i.e., incision.) The bedrock threshold here (770') probably controlled lake level in Cedarvale trough while the delta at Stop 4

(Saunders' gravel pit) was forming.

Though not as high as Niagara (120' vs. 160'), Clark Reservation falls is virtually identical to Horseshoe Falls of the Niagara in terms of both planform and size.

At this Stop we will consider the activation sequence of the "Syracuse" channels. All have dimensions requiring "Great Lakes" (Lake Warren) drainage. All were active in late Wisconsinan time. Most (all?) have had complex histories, involving more than one period of excavation.

Restricted (channelized) flow across the Onondaga/Butternut spur began with Smoky Hollow. Scour began at the 900' level, and the channel was abandoned when its floor (at the west-end entry) had been lowered to 790'. Reworked drift in delta deposits in Butternut valley shows that final excavation involved removal of fill from a channel predating the last glacial override. Origin of the cut-off "meander" loop is not well understood, but relict drift deposits in this loop are further evidence of complex history. The scour and delta surfaces between 800' and 900' in Cedarvale trough probably relate to a gradually falling lake controlled by the Smoky Hollow outlet.

Ice retreat soon opened a more northerly escape route through Clark Reservation, establishing an Onondaga-valley lake level controlled by the bedrock threshold above the falls (770'). Cedarvale deltas tied to this threshold include the one seen at Stop 4. Drainage evidently followed the retreating ice margin northward, scouring to bedrock, until Nottingham Road channel became active. The sill leading to the abandoned waterfall at the head of Nottingham channel stands at 700'.

Intermediate points of stabilization were the two abandoned waterfalls in the south wall of Rock Cut (760', 730'). These falls show that the eastern half of Rock Cut was open at this time. However, as discussed by Hand and Muller (1972), subsequent activation of Nottingham channel would not have been possible unless the western half of Rock Cut remained plugged, and a (drift? ice?) barrier separated the approach to Nottingham from the two Rock Cut plunge basins. Catastrophic *failure of this narrow barrier was invoked by Hand and Muller to clear Rock Cut and High Bridge channels to their present levels, creating prominent deltas at the eastern ends of these channels and abruptly lowering the lake level in Onondaga valley by 100'.*

Delta terraces in Cedarvale trough seem compatible with this scenario. They suggest that after a period of gradual decline from about 790' to 700' (corresponding to gradual lowering of bedrock thresholds between Clark Reservation and Nottingham), there was an abrupt drop to 660'-600'. None of the "Syracuse" channels could have provided suitable control for this latter (very extensive) set of deltas. However, if Rock Cut and High Bridge channels were cleared as proposed by Hand and Muller, they would have provided an over-deepened (slow-flowing) exit route to a level-control point still farther east, namely Pools Brook channel (590') or young Lake Iroquois beyond.

Other questions surround Meadowbrook channel, whose floor elevation (western end) is 550', essentially matching that of Rock Cut. Original cutting of Meadowbrook undoubtedly occurred a long time ago, but its graded floor and mild truncation of drumlins indicate that it carried at least some flow during final deglaciation. How could flow have been forced through Meadowbrook if Rock Cut had already been opened to the same level? (Indeed, a somewhat lower level, since evidently some material has been removed from the floor of Meadowbrook channel.) Hand (1978) invoked an otherwise undocumented oscillation of the ice front to permit clearing Meadowbrook prior to opening the western half of Rock Cut. Subsequent blockage of Meadowbrook by ice was then called upon to reactivate Nottingham Road channel and set the stage for catastrophic flushing of the western part of Rock Cut. A simpler and perhaps better alternative envisions a "base" discharge adequate to have some erosive capability even when divided between two major channels. (Channels east of Limestone valley would have been abandoned by this time, and flow from Rock Cut and Meadowbrook would have escaped directly out the northern end of Butternut valley.)

■ Return to NY 173.

47.6 0.2 ■ Right on NY 173.

49.5 1.9 ■ Continue straight on Brighton Avenue. (NY 173 turns left.)

49.8 0.3 ■ Right on Rock Cut Road, following signs to I-481.

50.5 0.7 ■ Enter I-481 eastbound. **STOP 6**.

Observe Rock Cut channel: 100-150' deep, 1000' wide (floor), 2 mi long, threshold elevation 550'. Entrance ramp and the Onondaga Resource Recovery facility are directly below where Great Lakes discharge must have flowed in its approach to Nottingham channel. At that time, this (western) part of Rock Cut must have remained full of drift or ice. The postulated barrier that prevented Nottingham discharge from diverting to the (cleared) eastern end of Rock Cut was located just beyond (east of) the Resource Recovery facility. Next come the two abandoned waterfalls spilling over the south wall. These provided the flow that cleared out Rock Cut from here on east, prior to activation of Nottingham channel. A trailer park occupies one plunge basin; the other (upstream) became partially filled by a boulder bar when the barrier failed, and is not easily seen from the highway.

Gravel quarrying operations at the east end of Rock Cut have removed much of the delta attributed to the brief episode of catastrophic discharge attending barrier failure.

52.6 1.1 ■ Exit I-81 (Jamesville Exit).

53.0 0.4 ■ Right (S) on NY 91.

53.1 0.1 ■ Left (E) on Woodchuck Hill Road.

You are climbing onto a remnant of the delta deposits dumped into Butternut valley during catastrophic flow from Rock Cut. Butternut Creek subsequently isolated this delta remnant and created the steep slope.

On the right side of the road, property of Dewitt Sportsmen's Club preserves original *configuration of the top of the deposit. Note the adverse slope of the broad distributary-like scour. To construct this "delta" (expansion bar?), flow in Rock Cut must have exceeded 65 ft!*

53.7 0.6 ■ Left on Will-O-Wind Drive.

53.75 0.05 ■ Left at "T" (Will-O-Wind Drive). **STOP 7**.

This is the top of the delta/expansion bar attributed to the Rock Cut flood. In the early 1970's, a large highway cut (now vegetated and uninstructive) exposed the full thickness (50' or more) of the NE-dipping foresets within this delta/bar.

The main point of driving through this development is to admire the 6-foot boulders used as lawn decorations. These particular boulders (chiefly Onondaga Limestone) were swept out of Rock Cut and stranded here on the top of the delta. Most, however, were swept to the lip of the delta, from where they rolled down the delta front to form a layer of 2-6' boulders several feet thick beneath the main foresets. The size of these boulders and the need to push them up the backside of this "delta" helped convince Hand and Muller of the reality of the Rock Cut dam burst.

53.8 0.05 ■ Right on Cedar Heights Drive.

54.3 0.5 ■ Left (E) on Woodchuck Hill Road.

■■■■■

Detailed Road Log ends here. To return to Hamilton,

Continue E on Woodchuck Hill Road to NY 92 (≈2 1/4 mi);

Right (SE) on NY 92, through Manlius, to US 20 (≈12 mi);

Left (E) on US 20 to NY 12B (≈15 mi).

Right (S) on NY 12B to Hamilton (≈5 mi).

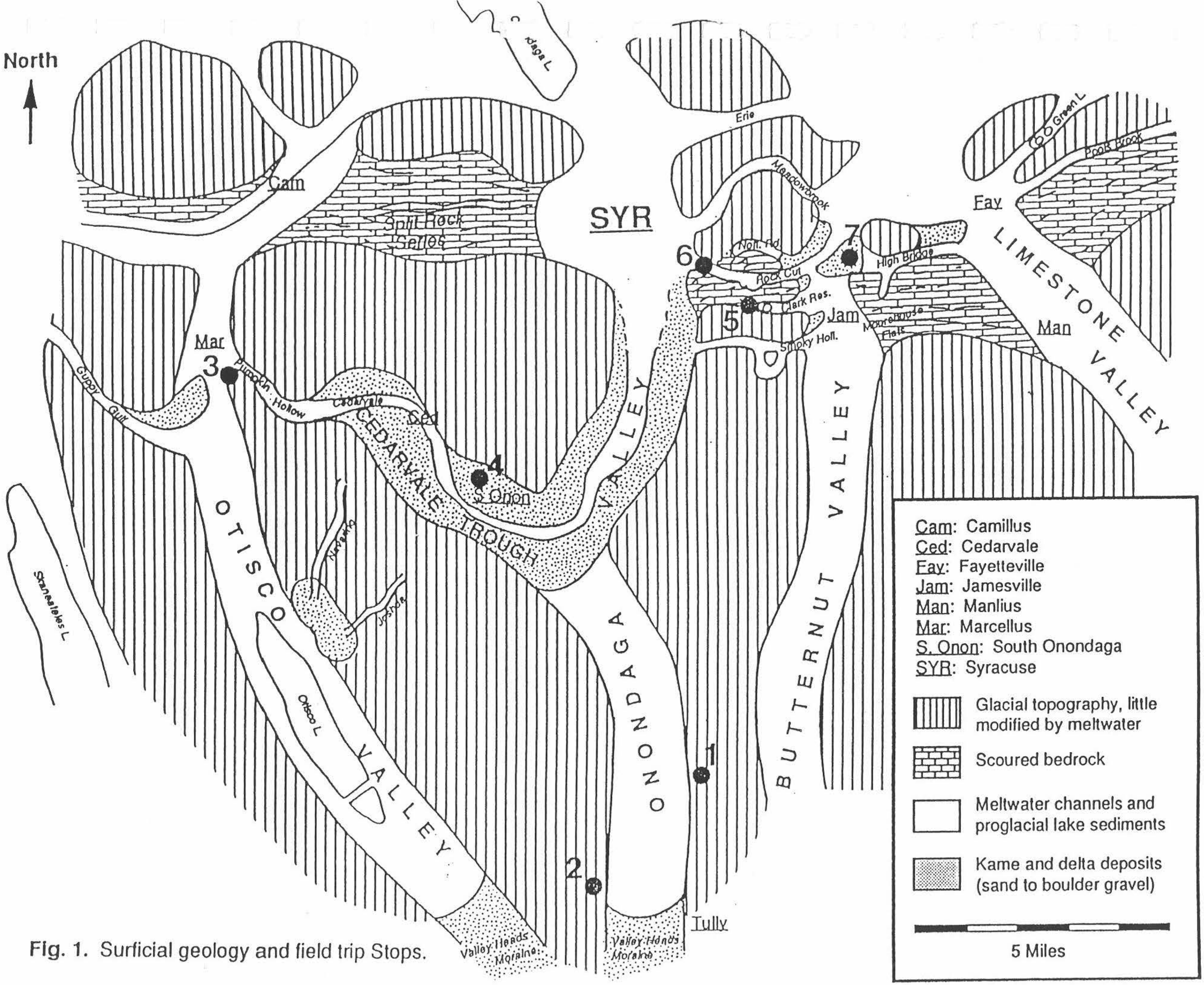

Fig. 1. Surficial geology and field trip Stops.

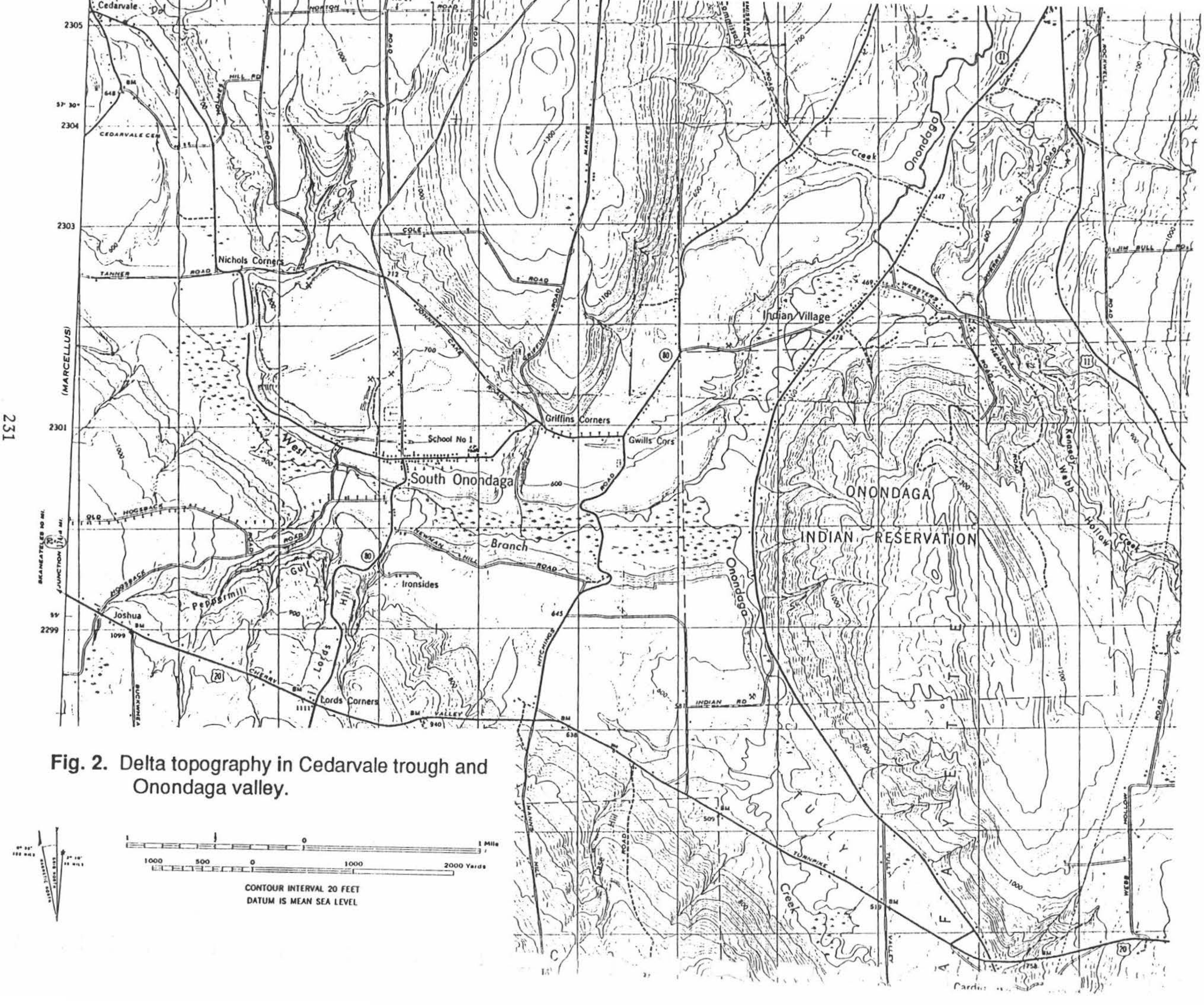

Fig. 2. Delta topography in Cedarvale trough and Onondaga valley.

Fig. 3. Topographic map of "Syracuse" channels.

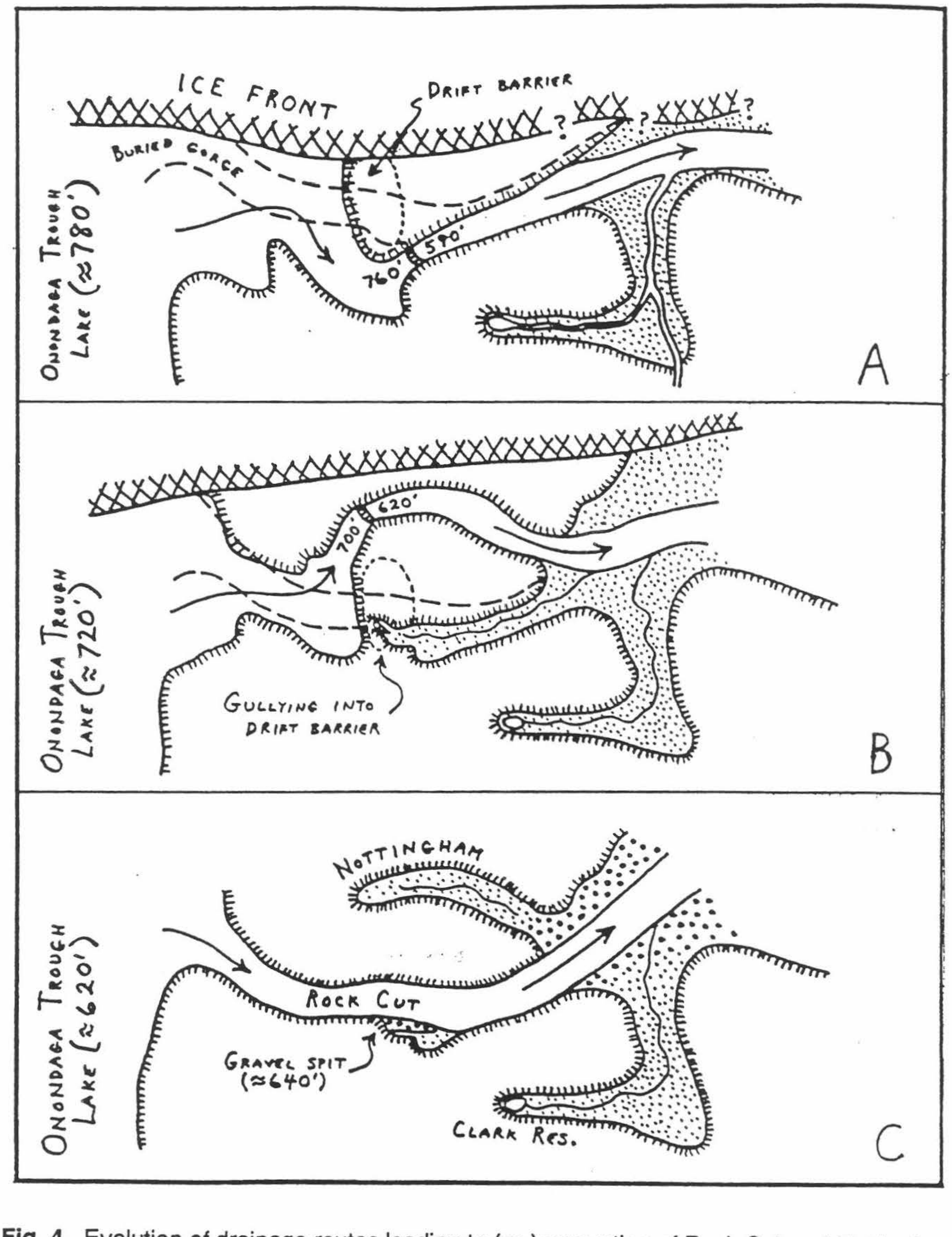

Fig. 4. Evolution of drainage routes leading to (re-)excavation of Rock Cut and Nottingham Road channels. (Slightly modified from Hand and Muller, 1972.)