QUATERNARY GEOLOGY OF THE GREATER SIXMILE CREEK WATERSHED

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July 30, 2015
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ABSTRACT

Discussion of the Quaternary geology of the Sixmile watershed is logically separated into two sections: the Sixmile-Willseyville Trough and the upper Sixmile drainage, both of which can be further divided into sub-units based on geological characteristics. The Sixmile Trough section displays evidence for 4 glacial advances based on morphologic and/or lithologic criteria. The oldest advance is associated with the broad U-shaped upper valley slope section and is possibly pre-Illinoian. The probable Illinoian age of an inner glacial trough is derived from the assumed Sangamon age of a very large interglacial gorge incised into the floor of that trough. The inner glacial trough is overlain by an array of mid-Wisconsin (Cherrytree stade) deposits that document a glacial advance that reached into the Sixmile Trough. An interstadial gorge was cut into the base of the Sangamon gorge, probably following the mid-Wisconsin glaciation but before the Late Wisconsin glaciation, which overrode the entire area and overprinted most of the earlier glacial features.

The ice front retreat from the Late Wisconsin glacial maximum (Nissouri stade) is best documented in the Willseyville Trough and upper Sixmile drainage. Well data indicate that the ice front during the Erie interstade did not retreat far north of the Sixmile-Willseyville trough-upper Sixmile junction, which would explain the single Late Wisconsin till in the Sixmile Trough. The subsequent Port Bruce re-advance produced the Valley Heads moraines, which are characterized by large outwash plains but few end moraines or lateral moraines on the interfluves. However, several such moraines and ice margin channels in the upper Sixmile drainage outline the shape of the Port Bruce ice front there. Ice stagnation following the Port Bruce advance led to extensive kame and kettle terrains behind the ice front maxima and to a small lake trapped between the Willseyville Trough and Upper Sixmile valley. A large delta fed sediment from the upper Sixmile basin into this lake. Till interbedded with the deltaic foresets demonstrate that active ice closed this lake at times. The lake drained, probably catastrophically, through a large channel, here termed the Willseyville channel, now marked by a series of wetlands separated by alluvial fans. A minor "Brooktondale" re-advance is marked by a till overlying the delta and by a lateral moraine that can followed from the east side of Inlet Valley across the interfluves into the Sixmile Creek valley and onto its northern slope. The Brooktondale re-advance is here correlated with the Hatfield event in New England and the Little Falls re-advance in the Mohawk valley, at about 13.25 ka BP.

An unusual channel, located at the front of this ice advance near the Brooktondale delta, changes its downstream direction 180° from southerly to northerly and cuts across and downward through the delta. It is most easily explained as an englacial to subglacial channel that drained NW under the ice of the Sixmile Trough. This would require subglacial drainage down the Sixmile Trough and northward along the Cayuga Trough into the Mohawk valley, which was ice-free at this time. Sub-glacial drainage at this time would explain the lack of lacustrine sediments in the southeast section of the Sixmile Trough. Subglacial drainage was apparently soon blocked and a proglacial lake formed in the Sixmile and Cayuga troughs because a deltaic or lake marginal, coarsening upward sequence of fine sand to gravel overlies the till in the northwest section of the Sixmile Trough. A planar cap of coarse gravel and cobble descends northwesterly along the Trough from an elevation of approximately 780’ at the 30’ dam to 600’ at Van Natta’s dam, indicating a rapid decreasing surface elevation of this proglacial lake. This decrease in elevation is attributed to the retreating Laurentide ice front, which is recorded by recessional moraines north of Ithaca.
INTRODUCTION

The Finger Lakes region of central New York provided an early testing ground for a number of concepts concerning the behavior of continental glaciers. Because some of the pioneers in this field at the turn of the 20th century were associated with Cornell University, a fair number of these early studies were drawn from observations in the area around Cayuga Lake.

Local observations were cited both in support of and in opposition to the idea that glaciation could cause massive erosion rather than merely sculpting existing landforms. Mullins et al. (1989) review this controversy in some detail.

Concepts of hanging valleys, interglacial gorges and through valleys were developed from observations during this period and by about 1910 the currently generally accepted model of the final, Late Wisconsin glacial stage and of the subsequent post-glacial history of this area had been fairly well outlined (Williams, et al, 1909).

This model includes a Late Wisconsin ice sheet that, at its maximum, covered all the local topography and extended into northern Pennsylvania. A subsequent northward ice retreat, with some complexities, was associated with a series of pro-glacial lakes that were trapped between the retreating ice front and moraines near the Susquehanna-Saint Lawrence watershed divide. Some of these lakes were precursors to the present Finger Lakes.

Studies of the Quaternary history in the region have added details and constrained the dates of some events during the Wisconsin Stage but interest in this subject greatly diminished after the early 20th century. On the other hand, significant advances during this time frame were being made in the understanding of glacial processes, based largely on the studies of modern glaciers. Of these processes, those associated with the sub-glacial hydrologic regime, which was not well understood when the Finger Lakes model was developed, may be of particular relevance in reinterpreting the glacial history of the Cayuga region.

To be sure, there have been a few, mostly quite recent studies that have questioned the still generally accepted traditional model. These include studies based on seismic reflection profiling and coring of the Finger Lakes (Mullins et al., 1996), which suggested to them that the Cayuga Trough had been eroded by sub-glacial meltwater to and possibly into bedrock during the last significant Late Wisconsin advance into that area (the Port Bruce Stade) and that the entire thick fill beneath the lake was deposited since then. Sub-glacial channels (Petruccione, et al, 1996) and drumlins (e.g. Shaw and Gilbert, 1990) north of Cayuga Lake were cited as evidence for massive sub-glacial water flow and erosion in that area. Conclusions of these studies remain contentious but suggest that the Late Wisconsin glaciation in this region might be profitably re-examined in light of the decades of knowledge obtained from studies of observed glacial behavior.

This paper presents recent field observations in the greater Sixmile Creek watershed (Fig. 1), which includes a wide range of glacial features ranging in age from at least as early as middle Wisconsin to Holocene. The Sixmile watershed is unusual in that it includes the site of a significant ice stream (Sixmile-Willseyville trough), which is also a hanging valley. This combination led to deep post-glacial erosion and to exposure of a wide range of both Late Wisconsin and earlier Quaternary deposits.

The greater Sixmile Creek watershed is here defined as that watershed plus several areas adjacent to it whose Quaternary histories are intimately related to this study. The largest of these adjacent areas is the headwaters of the Willseyville Creek watershed. The observations in the study also include seismic and borehole data not available to the early workers. All these observations were interpreted in light of modern glaciological studies, with conclusions compared to and contrasted with the traditional glacial history of this area.
Figure 1. Location map of study area, divided into 4 sub-areas based on distinctive geological characteristics. Political and geographic features noted in the study are shown, as is location of the study area in New York State.
REGIONAL SETTING

The Sixmile Creek watershed includes a glacial trough, here termed the Sixmile-Willseyville Trough, as well as quite different settings in the section of the watershed upstream from Brooktondale. The Sixmile-Willseyville Trough diverges southeasterly from the Cayuga Trough near the south end of Cayuga Lake (Fig. 1). Although the Sixmile-Willseyville Trough is the straighter extension of the Cayuga Trough north of this bifurcation, it was clearly secondary to the southern extension of the Cayuga Trough in volume of ice flow. The clearest manifestations of this relationship are that the bedrock floor of the Sixmile-Willseyville Trough "hangs" about 700 feet above that of the Cayuga Trough and that the Sixmile-Willseyville Trough is narrower.

Nevertheless, the Sixmile-Willseyville Trough was the site of major ice flow and contains one of the more pronounced "through valleys" in the region. It is intermediate in degree of glacial erosion between the Cayuga Trough and valleys such as those of Cascadilla and Fall creeks, which are oriented transverse to the general direction of ice flow.

The section of the Sixmile-Willseyville Trough from Ithaca to Brooktondale, which is termed the Sixmile Trough in this study, is relatively broad, with gentle valley sides and is now occupied by the lower section of Sixmile Creek. For several miles upstream from Ithaca the trough displays several bedrock gorges. Above these gorges, in which the city has a series of dams built for its water supply, bedrock is not exposed until the stream reaches Brooktondale.

Near Brooktondale, the Sixmile-Willseyville Trough turns southward, and from here is termed the Willseyville Trough. The Willseyville Trough becomes narrower southward and develops a more pronounced U-shaped cross section, with steep valley walls. The southern, Willseyville section of the Sixmile-Willseyville Trough extends past Willseyville, where it merges with the Danby Creek valley and continues southward. Only that section north of Willseyville is considered in this report.

Sixmile Creek crosses the eastern bedrock flank of the Sixmile-Willseyville Trough near Brooktondale and heads eastward just beyond Slaterville and then northward to its headwaters in the hill mass south of the Fall Creek valley (Fig 1). In effect, the upper Sixmile valley “hangs” with respect to the Sixmile-Willseyville Trough. The upper Sixmile Creek drainage also can be divided into several sections with different glaciologic characteristics. One section continues east of Slaterville in a shallow trough that continues into the Owego Creek drainage, whereas the other, containing the headwaters of Sixmile Creek, turns northward.

HISTORY OF INVESTIGATION

Reports concerning the glacial history of the Sixmile Creek watershed can be traced as far back as 1877 (Simonds, 1877), but observations of R.S. Tarr led to the development of the area’s first comprehensive treatment. Tarr (1894) recognized that the Sixmile Trough was a hanging valley with respect to the Cayuga trough and that, in addition to the post-glacial gorges that this condition engendered, there was an earlier, larger inter-glacial gorge, which required at least two periods of glaciation in this area. At that point in time, Tarr appealed to intense glacial erosion to explain the depth of the Cayuga trough, but in a subsequent paper (Tarr, 1904b), he had misgivings concerning the efficacy of glacial erosion, citing among other observations the apparent lack of erosion beneath the Late Wisconsin till and the V-shaped inner valleys of major glacial troughs. By 1909, however, Tarr (Williams, et. al., 1909) had come to the conclusion that, whereas the Late Wisconsin ice advance was associated with remarkably little bedrock erosion, earlier ice advances had been highly erosive and were responsible for much or most of the glacial geomorphology of the region.

In this same publication Tarr presented an extensive array of observations in the Sixmile
Creek watershed and effectively created the Quaternary geologic history that is still generally accepted. More detailed studies based on some of Tarr’s observations were made shortly thereafter, including those on ice marginal channels (Rich, 1908), the interglacial gorges of lower Sixmile Creek (Rich and Filmer, 1915) and the Late Wisconsin evolution of Sixmile Creek above Slaterville (Hausman, 1918).

The next major figure in the history of investigation in the study area was O. D. von Engeln, who presented a compilation of his observations in his book, "Origin and Nature of the Finger Lake Region” (von Engeln, 1961). In that volume, von Engeln presented a panoply of observations made subsequent to those of Tarr, but arrived at the same general history. Von Engeln neglected the work of Victor Schmidt (1947) on the pre-Late Wisconsin varved clays and associated lithologies found just upstream of the post-glacial gorges on Sixmile Creek. These deposits were recently described by Karig and Miller (2013).

Other recent workers whose publications include at least references to the Sixmile Creek watershed include E. H. Muller, A.L. Bloom and T. S. Miller. Muller (1957, 1965) commented on various glacial features and presented new chronologic data, and Muller and Cadwell (1986) generated the Finger Lakes sheet of the surficial geologic map of New York. Bloom (1972, 1986) included new observations in field trip guides to the Cayuga Lake area. Miller, through his investigations of aquifers of Tompkins County, has produced several, more detailed maps of the local surficial geology (e.g. Miller, 2009, Miller and Karig, 2011).

This study was centered on field observations in the Sixmile Trough (Plate 1), from 2005 to present, primarily involving transects along most of the tributaries to Sixmile Creek. Less inclusive, site-specific field observations were made in the Willseyville Trough and in the upper Sixmile watershed. Field observations were augmented by well logs, shallow coring and seismic data, some of which were acquired for this study. Both refraction and passive reflection seismic data were either led by or done in cooperation with Todd Miller of the U.S. Geological Survey, which supported this study in many ways.

PRESENTATION OF DATA

This study of the glacial geology of the Sixmile Creek watershed comprises two streams of data: landforms and lithologies. The first data stream involves glacial and related landforms, both those that largely shape the present landscape, and those now significantly modified by erosion or buried under younger deposits. These buried landforms are interpreted using subsurface information, primarily seismic profiles and well logs.

The second data stream involves lithologic units, not only of glacial deposits but also of related fluvial and lacustrine sediments. These are observed both in exposures and with well data. Lithologies related to glaciation are notoriously difficult to organize. Because of rapid lateral and temporal variations in deposition, superposition of units is not often observed and an absolute chronological organization is hindered by a paucity of absolute or relative ages. By far the most of the lithologic data for this study are from lower Sixmile Creek, where post-glacial stream erosion has cut deeply into the Quaternary section.

A major problem and an objective of this study is the correlation of lithologies with landforms, both spatially and chronologically. In some instances the correlation is straightforward, whereas in other cases it is presently impossible, in large part due to lack of chronologic control. Here the landforms are described first, followed by description of lithologies. Integration of the two data streams, to the extent possible, follows.

This organization is applied to three areas within the study area because the glacial geology within each of these (Sixmile Trough, Willseyville Trough, and upper Sixmile watershed) is relatively similar and differs significantly among them. When possible, landforms and lithologies are described from
oldest to youngest.

SIXMILE TROUGH

Workers as early as Tarr (1904) recognized at least two periods of glaciation in the Ithaca area and suspected more from the morphologies of interglacial gorges and valley cross sections. Multiple glaciations in North America are now recognized from marine and other data for about the past 2.7 my (e.g. Haug et al., 2005) but, in general, most evidence for earlier glaciations has been removed by subsequent advances. Nevertheless, evidence is preserved in either the landforms or the lithologies for at least four glacial invasions into the valley containing the Sixmile Trough.

LANDFORMS

Pre-Glacial Valley
The valley slopes of the Sixmile trough show obviously different shapes from top to bottom, as has been long recognized (Rich and Filmer, 1915, von Engeln, 1929). The uppermost slopes are gentle and have been regarded as remnants of the pre-glacial topography of a fluvial V-shaped valley (Plate 2, Section E-E’). Extrapolation of these slopes on the profile of Section E-E’ to the valley center suggests a stream elevation there to be near 1000’. This extrapolated elevation is about the same as the elevation of Cascadilla Creek at an equivalent distance from the Cayuga Trough. Cascadilla valley trends almost perpendicular to the direction of ice flow and is presumed to have undergone minimal glacial deepening. Fall Creek, which has an intermediate orientation with respect to the ice motion, appears to be at a bit lower elevation. Westward extrapolation of these tributary gradients suggest an elevation of roughly 700’ to 800’ at the center of the pre-glacial Cayuga Trough near Ithaca, which is in general agreement with the conclusions of Tarr (1904) and von Engeln (1961).

Outer Glacial Trough
Below the gentle uppermost slopes on both sides of the Sixmile Trough are bands of concave upward slopes that are quite steep at their upper margins and that define a broad U-shaped trough (Plate 2, Section E-E’) when interpolated across the valley. These bands lie between 1300’ and 1000’ on both sides of the valley and the interpolated slopes suggest a trough elevation of 900’ near German Crossroad (Plate 2, Section E-E’). This trough is defined by bedrock, covered by a thin mantle of till of Late Wisconsin age, and can reasonably be interpreted as a result of erosion during one or more glacial periods. This feature is here termed the “outer glacial trough”, to differentiate it from another, inner bedrock trough, described below.

Section E-E’ indicates that a significant amount of bedrock must have been removed during the development of the outer glacial trough but that it was more by widening than by deepening of the pre-glacial fluvial valley. The outer glacial trough appears to flair and become less pronounced as it approaches the Cayuga Trough.

Inner Glacial Trough
Another U-shaped bedrock trough is clearly defined within the broad outer glacial trough by a sharp change in bedrock slope along the southwest side of the Sixmile valley between the 60’ dam and German Crossroad (Plates 1 and 2). The boundary between the inner and outer troughs is much more subtle on the NE flank of the Sixmile Trough, but is defined by a slight change in bedrock slope. That the inner glacial trough is cut down into the base of the outer trough indicates that the former is the younger feature. Lack of exposures and of subsurface control prevents the identification of this boundary further to the southeast along the Sixmile Trough.

The longitudinal profile of the inner glacial trough, or of the combined glacial trough southeast of where the two can be differentiated, is quite flat (Fig 2). From the 60’ dam to the transition into the Willseyville Trough the floor
Rises only from 700’ to about 750’. Northwestward from the 60’ dam, the trough floor progressively steepens and becomes difficult to define downstream of Van Natta’s dam.

**Gorges**

The Sixmile Trough is incised by bedrock gorges of 3 different ages. Each of these gorges was cut following a glacial stade that left the Sixmile Trough “hanging” above the Cayuga Trough. Stream erosion, attempting to bring Sixmile Creek to grade with the Cayuga valley, either re-excavated pre-existing drift-filled gorges or cut new gorges in bedrock.

**600’ Gorge**

The oldest and largest of these gorges was first identified by Tarr (1904) and was described in detail by Filmer (1912) and Rich and Filmer (1915). They termed this feature the 600’ gorge, based on the width between its generally very steep walls. The 600’ gorge can be traced almost continuously from the Columbia St. footbridge to the 60’ dam in exposures (Plate 1) and in the subsurface by drill holes (Hatch, 1940) and refraction data (Miller and Karig, 2010) at least to Banks Rd (Plate 1). How much further upstream this gorge extends is uncertain, but a 309 ft. deep drill hole south of Brooktondale that did not reach bedrock almost demands that it extends into the Willseyville Trough.

Along most of its exposed length the gorge has been re-excavated by post-glacial Sixmile Creek, but adjacent to the 30’ and 60’ dams the stream degraded through the Late Wisconsin till outside the 600’ gorge, which resulted in post-glacial bedrock gorges and in sections of the 600’ gorge that remain filled with glacial, fluvial and lacustrine sediments (Plate 1 and Section C-C’ of Plate 2).

The reach of the 600’ gorge between Van Natta’s dam and the 60’ dam is characterized by very steep walls, often nearly 100’ high, and a relatively flat floor. Widening by stream undercutting is actively occurring in several places along the 600’ gorge. In several places, as on the south side of the reservoir behind the 30’ dam, tributaries to the 600’ gorge also appear to

![Figure 2. Longitudinal Profiles of glacial and fluvial systems along the Sixmile-Willseyville Trough. Profiles are based on data from exposures, well logs and seismic results, all extrapolated to the estimated thalwegs of the respective systems, which are not necessarily coincidental or in the center of the valley. Cross-sections are shown on plates 2 and 4.](image-url)
be incised into bedrock (Plate 1).

The floor of the 600’ gorge is only slightly above present stream level at the 60’ dam and rises only slightly above stream level downstream but, at the post-glacial gorge where Van Natta’s dam was built, the floor forms bedrock terraces about 70’ above the creek (Fig. 2). Cultural development makes it impossible to identify the 600’ gorge further downstream of the Columbia St. footbridge. The walls of the 600’ gorge also become less steep downstream from Van Natta’s dam where the gorge assumes more of a flaring U-shaped section (Plate 2, section A-A’). The gradient of the 600’ gorge also progressively increases downstream from about the 60’ dam (Fig. 2).

The gradient of the 600’ gorge above the flaring and steeper section is about same as that of the inner glacial trough and much less than that of the present stream (Fig. 2). The steeper, downstream section has a gradient estimated as 0.0137 (Rich and Filmer, 1915) or 0.0123 (this study). The profile of the 600’ gorge, even the steeper downstream section, would project well above the present level of Cayuga Lake and far above the Cayuga trough bedrock elevation, which led Rich and Filmer (1915) to conclude that the 600’ gorge was developed in a hanging valley following pre-Late Wisconsin glaciation. The 600’ gorge is cut into the inner glacial trough (Plate 2, Sections C-C’ and D-D’) and is therefore younger than that feature. The size and extent of this gorge reflects a prolonged period of erosion, which implies either an interglacial period longer than post-glacial time or repeated periods of erosion or probably both.

200’ Gorge

A second, interstadial gorge was identified by Rich and Filmer (1915) from the point where Sixmile Creek debouches into the Cayuga Trough upstream to Van Natta’s dam (Plate 1). This gorge was termed the 200’ gorge, again for its width, and displays almost vertical walls for its entire exposed length. Von Engel’s (1929) identified the 200’ gorge immediately upstream of Van Natta’s dam on the north side of Sixmile Creek, but no evidence has been found for it further upstream. Up to within a few hundred yards below Van Natta’s dam this gorge has been re-excavated by post-glacial Sixmile Creek. South of the reach of Sixmile Creek that contains Van Natta’s dam and the post-glacial gorge in which that dam was constructed, the 200’ gorge is filled with sediment, of which the upper 1/3 is till, overlying a fluvial section.

That the 200’ gorge is incised into the floor of the 600’ gorge (Plate 2, Sections A-A’ and B-B’) demonstrates its younger age and its much lower elevation indicates that the base level in the Cayuga Trough must have dropped significantly after the creation of the 600’ gorge and before that of the 200’ gorge. The 200’ gorge must have been created before the final Wisconsin glaciation because till from that event was deposited within the gorge. Erosion along sections of Sixmile Creek that impinge on the 200’ gorge walls is widening this feature and creating a bench at the present stream level.

The floor of the 200’ gorge is below the present creek level at least as far upstream as the Columbia St. footbridge. Boreholes drilled for the construction of that bridge show that the gorge floor is 20’ below present stream level at that point. Boreholes on the fan surface at the mouth of the Sixmile Trough demonstrate that the bedrock gorge floor is about 50’ below the present stream level (Plate 1). A proprietary map without supporting borehole locations (Lawson, 1977) shows the gorge extending southwesterly along the flank of the Cayuga Trough but a number of recently drilled construction boreholes in this area precludes the existence of this gorge extension. Borehole logs demonstrate that the Sixmile bedrock gorge ends against the NNE-trending slope of the Cayuga Trough (Plate 1). The available borehole control indicates that the 200’ gorge has an average gradient of about 0.03, which is much steeper than that of the present stream. Projection of this steeper gradient upstream of where it is last identified suggests that the 200’ gorge would intersect the base of the 600’ gorge and the present stream valley floor not far upstream of Van Natta’s dam (Fig. 2). The
elevation of lowest control point on the 200’ gorge profile is more than 30’ below the present level of Cayuga Lake implying that the base level for the creek at the time when the 200’ gorge was cut was well below that at present.

Post-glacial Gorges
Late Wisconsin glaciation left thick deposits of till in the Sixmile Trough, the surface of which was far above the base level of Sixmile Creek at Cayuga Lake. The post-glacial re-establishment of a NW-flowing Sixmile Creek resulted in channel degradation into this till, which has proceeded to the stage where the channel has reached bedrock along much of the northwestern half of the Sixmile Trough. Over most of this section of the Trough the stream has re-excavated older gorges; the 200’ gorge from Ithaca almost to Van Natta’s dam and the 600’ gorge between that dam and almost to the 60’ dam. However, in the vicinity of both these dams and at the 30’ dam the stream has cut short, post-glacial bedrock gorges (Plate 1). The lowermost post-glacial gorge has been cut into the floor of the 600’ gorge (Plate 2, Section B-B’), whereas the other two have been cut into the base of the inner glacial trough (Plate 2, Section C-C’). Each of these post-glacial gorges is very narrow and V-shaped, with a floor not much wider than the stream channel (Fig. 3). There is no evidence that these gorges were cut during more than a single erosional cycle following the last retreat of the ice.

Late Wisconsin Till Surface
The dominant landscape feature in the Sixmile Trough is the surface here interpreted to be the top of the till that was laid down during the Late Wisconsin glaciation. Previously this surface has been implied to be the floor of post-glacial Lake Ithaca (e.g. Williams, et al., 1909) but mapping during this study demonstrates that it is a till surface. More detailed justification of this interpretation is presented in the section on lithologies.

This surface has been extensively dissected by post-glacial stream erosion but remnants remain as terraces in the valley, especially along its northeastern side (Plate 1). These remnants allow the reconstruction of the till surface across the valley, downstream about as far as Van Natta’s dam, as shown by the contours on Plate 1. At the edges of the valley this till surface steepens and becomes the top of a thin till sheet that covers the uplands.

This upland till sheet, especially on the interfluve SW of the Sixmile Trough, shows definite SSE-trending lineations on Lidar hillshade images (Fig. 4). Individual lineations typically have heights of 10± ft, widths of 300-400 ft and lengths of several thousand ft, and are almost certainly megaflutes that show the direction of flow during the last ice advance across this area.

The till surface in the Sixmile Trough is a remarkably smooth surface with a broad U-shaped cross-section (Plate 1). In particular, no kame features can be identified, in contrast with their abundance in the Willseyville Trough. There are, however, a few landscape features that were constructed on this till surface, which are described below.
Lateral Moraines and Ice Margin Channels

Lateral moraines can be mapped discontinuously on the ridges north and south of the Sixmile Trough but have not been recognized on the till surface in the floor of this trough. The most extensive expression of these moraines was by Tarr (Williams et al., 1909), who was able to more easily observe these features when the land was more completely cleared for agriculture. Renewed forest cover and residential development now greatly inhibit such visual identification but recent Lidar mapping, with both 2’ contours and hillshade processing, highlights some of Tarr’s moraines and reveals others. Tarr mapped three distinct morainal loops and many short moraine segments south of the Sixmile Trough, but only the two of these morainal systems that can be identified with the Lidar data are discussed here.

The most prominent and highest of these morainal loops is that described by Tarr (Williams et al., 1909, p.150), which can be mapped from the east flank of the Cayuga Trough, into the upper Buttermilk Creek drainage and over the divide between that drainage and into the Sixmile valley at an elevation near 1430’ (Plate 1, Fig. 4). It can be followed east-southeastward for another 4000’ with the Lidar data (Fig. 3), largely in agreement with Tarr’s interpretation. Tarr has this moraine dropping eastward into the Sixmile Trough, approaching the valley center in several splays between Middaugh Rd and Brooktondale, from which

Figure 4. Lidar derived hillshade image of the Sixmile Trough, showing the “arrowhead” hill shapes, moraines (marked by dots), and megafluting on the interfluve south of Sixmile Creek.
area he continues the feature northwestward and into the Cascadilla valley. No evidence for this extension is seen on the Lidar data and the most prominent of Tarr’s splays was interpreted in this study as an erosional remnant of till.

Instead, a continuation of the same general slope (0.01) suggests that this moraine can be extended to a moraine segment that parallels an ice margin channel above Coddington Rd near 42° 22.9’N, 76° 25.5’W (Plate 1). This segment can be followed for about 1900’ and drops southeasterly along its length from an elevation of 1300’ to 1200’ or less. At its southeastern end the channel turns sharply northeastward and becomes a gully that trends down the dip slope, and along which bedrock is intermittently exposed almost to Coddington Rd. This gully is most easily interpreted as a sub-glacial chute. Bedrock is also exposed at several places along both sides of this marginal channel, but the northeastern flank is basically a till moraine that appears to continue a short distance beyond the sub-glacial chute.

Short possible moraine segments lead from this location to the complex area where upper Sixmile Creek joins the glacial trough and to several more sections that can be correlated with this moraine. This area is discussed in the Willseyville Trough section. Part of what is probably the same moraine is a well-defined segment mapped on the crest of the ridge between Sixmile and Cascadilla creeks, at the same 1420’ elevation and opposite the morainal crest on the south flank.

Another morainal feature that was identified in the Sixmile Trough during this study is a feature that appears to be a combination of lateral moraine and ice margin channel. This channel/moraine, which wraps around the nose of South Hill on the Ithaca College campus, was identified by Tarr (Williams et al., 1909) and further described by von Engeln (1961). This feature can be traced on current USGS 1:24,000 topographic quadrangles from the east flank of the Cayuga Trough at 42° 24.9’N, 76° 30.1 W and at an elevation of about 1030’, around South Hill and southeasterly along the flank of the Sixmile trough for over 10,000’ to about 42° 24.4’N, 76° 28.2 W and an elevation of about 970’ (Plate 1). The 2’ contours of the recent Lidar topography suggests that the feature continues further SE to 42° 24’22.1”N, 76° 28’06.1”W with an elevation of 962’.

This feature has been destroyed on the Ithaca College campus and to the southwest by construction but this section is well described by Tarr (Williams et al., 1909. p. 163) as “a well-defined marginal channel, about 100 yards wide, with rock walls on both sides and a flat, swampy bottom…but toward the northeast it develops abruptly into a terrace, with a rock cliff 30 to 40 feet high…swinging eastward around the hill nose.”

The channel in the Cayuga Trough has an average northward slope of 0.006, which is opposite the slope that the glacial surface in that trough must have had. This is an argument that the channel was a fluvial feature that must have become subglacial as it wrapped around the nose of South Hill. Its source may have been a proglacial lake but this channel could also have been fed by fluvial sources south of the ice margin and have drained into that margin.

This feature is still well preserved to the southeast of Ithaca College, where, for most of its length, it is a terrace, possibly with several levels. Near its southeast end the feature develops into a ridge backed by a swale. Both aspects appear to be superimposed on the till surface rather than being incised into it. No bedrock is exposed along the terrace or in the swale behind ridge segments but is exposed in a gully beneath a thin (10’) cover of till a few hundred feet upslope of one swale. The average slope of the feature along the flank of the Sixmile trough is .008 toward the southeast.

On both the terrace and ridge are many large angular blocks of local bedrock, which contrasts with the more mixed last content of the local till. The size and abundance of these blocks appears to increase toward and near the Ithaca College campus and most likely were derived from that area, where Tarr indicates that this feature was incised into bedrock. Although this feature was
probably a subglacial channel along its Ithaca College section, it appears much more likely to have become a lateral moraine to the southeast, as was suggested by Tarr. The lack of a sedimentary deposit at the end of the feature also supports a morainal interpretation, at least for the southeastern end. A group of gullies below the morainal section, seen clearly on the Lidar topography, may have originated as sub-glacial chutes that drained water from the channel into the ice.

A moraine at about the same elevation (1010-1020’) and probably related to the same ice front is clearly seen on Lidar data (Fig. 3) on the interfluve NE of the Sixmile Trough from near the intersection of Pine Tree and Snyder Hill roads, and trending northeastwardly well past Game Farm Rd. This feature was interpreted to be a wave-cut shoreline of pro-glacial Lake Ithaca by Tarr (Williams et al., 1909) and von Engeln (1961) but it consists primarily of segments of a single ridge that slopes to the NE, which is difficult to interpret as a beach feature.

**Enigmatic Channel**

Of particular interest is a channel that roughly parallels Sixmile Creek on its north side upstream of Burns Rd. (Plate 1) but about 50 ft above the present Sixmile channel. This channel, as shown by the 2’ Lidar-derived contours, is very broad and flat-bottomed and is now largely occupied by a wetland. The upstream end of this channel is truncated by the present Sixmile Creek channel and the entire channel lies within a swale in the till surface, the bottom of which is about 50’ lower than the general till surface. The wetlands end downstream just east of the power line/pipeline corridor but the wide, flat-floored aspect of this channel continues westward several hundred yards to at least 76°26’58” W. Approximately 300 yds further northwest is a small tributary to Sixmile Creek, part of which anomalously trends parallel to the valley slope and has sections with a wide flat floor. This section is probably a part of the same channel, now significantly eroded by subsequent stream degradation, because of its similar character and because the elevation of the best preserved remnant lies along a gradient of .016 from the major section of the channel, which has that same gradient.

Coring in the channel floor and observation of the area where Sixmile Creek has truncated this channel indicate a lack of any coarse fluvial sediment on the channel floor, where till occurs beneath a very thin organic layer. The lack of a significant fluvial substrate and even the existence of a wetland in this channel are anomalous given its high thalweg gradient. This channel might be an early drainage developed on the till surface shortly after it became ice-free or it might even be a subglacial Nye channel. An exposure, about 150 yds downstream from the point where this channel narrows and exposes till in the occupying stream, displays bedded silt overlying a clast rich diamictite that is strikingly different from the underlying clay-rich till. Clasts are rounded and largely of local origin. It is possible that the sediments in this exposure are somehow related to the channel.

**“Hourglass” Tributaries**

The three largest tributaries that enter Sixmile Creek from the south along the lower Sixmile trough have a tripartite nature that merits discussion. These include the two tributaries that parallel Burns Road on either side and one that parallels German Crossroad (Fig. 5). All these head near the top of the ridge marking the southwestern edge of the watershed as deeply incised channels, each with several branches. All these tributaries are also deeply incised where they cross the glacial fill of the inner glacial trough, but all appear as very shallow channels that barely cut into bedrock where they cross the lower, flatter section of the outer glacial trough.

The upper sections of these tributaries expose bedrock along parts of their courses but reveal till in other parts. This demonstrates that the upper sections preexisted the Late Wisconsin glaciation, which partly filled them, and that their present
condition represents partial post-glacial exhumation.

The lower sections are readily explained by post-glacial erosion of relatively non-resistant Quaternary sediments resulting from the degradation of the main Sixmile Creek channel. The explanation of the poorly developed middle sections is anything but straightforward. One possibility is removal of a once larger channel by erosion of the bedrock of the outer glacial trough by Wisconsin or earlier glaciation. A second possibility is that the reaches of these streams that crossed the flatter terrain never eroded a significant bedrock channel. The present till surface does display a subtle depression along some parts of these reaches. The most appealing possibility is that larger bedrock channels still exist across the flatter section of the outer glacial trough but remain buried beneath Wisconsin till because the post glacial tributaries found new courses across this till. Unfortunately, to date no such channels have been identified in the sparse well data from this area.

**Pro-glacial Sediment Surfaces**

Between Van Natta’s dam and the 30’ dam are exposures of silt, sand and gravel that overlie till and form local highs along both sides of Sixmile Creek, but much more extensively on the south side (Plate 1). These clearly once formed a single continuous sediment body that has been dissected by Sixmile Creek and its tributaries, which have eroded through these strata and into the underlying till.

Detailed Lidar topography shows that the larger sediment remnants have flat tops sloping northwesterly, with individual slopes and an overall slope of 0.04 to 0.05, from the 762’ top of the hill south of the 30’ dam to the 602’ top of the quarried hill south of Van Natta’s dam. With this slope the surface of the sediment body would intersect the top of the till at about 780’ or just upstream of the 30’ reservoir (Fig. 2). Two knobs northeast of the reservoir behind the 30’ dam at this elevation protrude above the general till contours, appear to be capped with gravel and probably constitute the upstream edge of this sediment. A flat surface at an elevation of about 800’, just SW of the City Reservoir, may be another section of this pro-glacial feature but, as explained later, has a different stratigraphy.

An isolated terrace underlain by somewhat similar post-glacial sediments lies just southwest of Sixmile Creek between Clinton and Aurora streets (Plate 1) and slopes westward from 478’ to 470’. Its location and slope could define a flatter section of the pro-glacial sediment body (Fig. 2) but the underlying stratigraphy is quite different.

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*Figure 5. “Hourglass” tributaries along the southwest side of Sixmile Creek valley. The watersheds of the upper, pre-late Wisconsin headwaters are in yellow and the post-glacial downstream sections are in green. The narrow watershed areas between them are associated with very shallow bedrock valley sections.*
**Alluvial Fans**

Along the northeast side of the lower Sixmile valley are two-fan shaped features that lie where the valley side slope sharply decreases downward. The larger and better developed of these is where Besemer Hill Rd meets Slaterville Rd. The other, which has been largely removed as aggregate, is where the Brooktondale Rd meets Slaterville Rd. (Plate 1). These features overlie till and were identified as deltas related to proglacial Lake Ithaca by Tarr (Williams, et al., 1909), but are more likely to be alluvial fans because of their shape, their elevations and their internal structure, which is described later. Rather than having flat tops, the features are more nearly conical. Their heads are well above 980' and correlate closely with the points where the tributary gradients decrease onto the valley floor.

Smaller examples of probable fans were also observed along the tributary from the south that parallels German Crossroad. A series of fan-like lobes on one or both sides of the present incised channel rise from an elevation near 850' to well above 1000’. These lobes are clearly composed of fluvial sediment, but no internal structure could be seen. There may be similar features along other tributaries that were not investigated, as suggested by similar lobe-shaped topography.

A gravel-rich cap or apron a few feet thick, which also was interpreted as deltaic by Tarr, overlies the till surface in many places along the northeast side of the Sixmile valley. The relationship of the apron to the fans is unclear but both were most probably sourced from the valley hillsides. The Lidar contours of the apron adjacent to the fans is near the junction of Brooktondale Rd and Slaterville Rd show a fan-like shape, emanating from the same tributary as does the fan and suggesting a common origin.

The most prominent alluvial fan in the area has formed where Sixmile Creek enters the Cayuga Trough. This fan, actually a compound feature, is now covered by the City of Ithaca but its geometry is clearly defined by the 2’ Lidar contours.

**Post-glacial Fluvial and Related Features**

Re-establishment of a northwesterly draining Sixmile Creek has led to erosion of the late Wisconsin till through such processes as channel degradation, slumping and hillslope creep. A dendritic pattern of tributaries to Sixmile Creek has developed in the thick till of the Sixmile Trough, especially along the northeast side of the valley. Several stream terrace levels occur along the channels of Sixmile Creek and its tributaries reflecting post-glacial degradation. Channel aggradation occurred during the 19th and early 20th centuries along these channels due to agricultural activity on the steeper slopes and uplands, followed by the current degradational channel regime as the watershed reverts to a more forested condition (Karig, 1999). Rotational slumps are abundant along the oversteepened slopes produced by stream degradation in the clay-rich till.

**LITHOLOGIES**

**Pre-Late Wisconsin Sediments**

Pre-Late Wisconsin sediments are exposed along Sixmile Creek and in tributaries entering from the south, from the reservoir behind the 30’ dam upstream almost to German Crossroad (Fig. 6). These include a possible Illinoian till and an array of middle Wisconsin sediments.

**Illinoian? Till**

What are probably the oldest Quaternary sediments in the study area are currently exposed just upstream of the silt dam along the north bank of Sixmile Creek. This diamicct-dominated unit probably lies directly on the bedrock floor of the inner glacial trough although this contact is not exposed. Schmidt (1947) observed this diamicct on the south side of the creek at his “high bank”, downstream of the present exposure, which would place the unit directly on bedrock that is now, but not then, exposed on the creek bottom. The unit is overlain by mid-Wisconsin sediments along a low angle disconformity.
A combination of Schmidt’s data and observations from this study indicate that this diamicton is quite variable both vertically and laterally, but everywhere has neither calcareous clasts nor calcareous cementation and is highly consolidated. Upstream (southeastward), the basal diamicton is composed primarily of unsorted angular clasts of the local bedrock with a silty to fine sand matrix and grades upward into fluvial sands and gravels with more rounded clasts. The downstream exposure at the high bank is no longer visible but the diamicton clasts there were reported to be dominantly round and to include a higher fraction of exotics, some of which had weathered rinds. These were interlayered with “crudely sorted clay, sand and fine gravel” (Schmidt, 1947). The diamicton described by Schmidt was exposed less than 5’ above the section of the creek bed where bedrock is presently exposed (Fig. 6). This unit almost certainly comprises a till and related fluvial sediments. Its maximum exposed thickness is about 15’ but must thin downstream to less than 5’ where bedrock is exposed. Bloom (1972) suggested that this unit was Illinoian in age but discussion of this conclusion is here postponed until more relevant data are presented.

Mid Wisconsin Sediments
Along and south of Sixmile Creek, from west of the 60’ dam and upstream for approximately 2 km is a lens of mid-Wisconsin sediments lying between bedrock of the inner glacial trough and Late Wisconsin till (Plate 1, Fig. 6). This mid-Wisconsin assemblage was discovered by Schmidt (1947) and described in more detail by Karig and Miller (2013). Here that description is summarized and augmented with observations made subsequent to those in that publication. The mid-Wisconsin assemblage consists of 3 lithologic units: a lacustrine clay sequence, a sand and gravel body and a till. These lithologies define a mid-Wisconsin glacial advance that trapped a proglacial lake to its south and that possibly stopped in this area (Fig. 7).

Of these units only the lacustrine clay was recognized and studied by Schmidt (1947, 1996), who divided this sequence into 4 varve series separated by gravel beds, which he interpreted as stream deposits. Of Schmidt’s varve series, the lowermost (series 1) are clearly varves, with couplets roughly increasing upward in thickness from $\frac{1}{4}$” to 1”. These varves are interpreted to have been deposited in a proglacial lake in front of a southward advancing ice front (Schmidt, 1947; Karig and Miller, 2013). The overlying 3 series of lacustrine sediments consist of alternating red and gray beds ranging in thickness from 0.1” to over 2’ (Fig. 8A) but are not obviously varves. They might instead represent different sediment sources; the gray beds from local sources and the red beds from Silurian shales to the north, transported south by the advancing ice front.

The gravel beds interbedded with the lacustrine clays are poorly sorted mixtures of silt, sand and platy, but rounded pebbles, mostly in the 0.5” to

Figure 7. Longitudinal section through Mid-Wisconsin strata illustrating the relationships among the various mid-Wisconsin units (from Karig and Miller, 2013). Section line shown on Fig. 6.
Figure 8. Lithologic components of the Mid-Wisconsin sediments south of the Silt dam on Sixmile Creek; A. Varved clay of unit 1 (proglacial lacustrine sequence) showing a thick silt/sand bed with organic layer at its base; B. Thin bedded lacustrine clay and silt of unit 1 with tongues of angular clast gravel from adjacent bedrock; C. Gravel in unit 2 (sub-aqueous fan), composed of exotic round cobbles showing imbricate clast structure; D. Deformation till of unit 3. Highly contorted bedded coarse sand and “floating” masses of red clay.
2” size range. About 90% of the clasts are of local origin (Appendix 2; bags 10, 11, 44, 45, 46, 67). Instead of fluvial deposits as interpreted by Schmidt, these gravels are almost certainly mass flow deposits transported from the edge of this pro-glacial lake, most likely from deltas.

Both at the base of the lacustrine sequence and at the top of the gravel (actually a turbidite) between the 3rd and 4th “varve” series are thin beds or lenses of organic-rich material, mostly plant fragments but also insect elytra, from which 12 radiocarbon ages have been obtained (Appendix 1). These ages range from 22 ka to 42 ka, which led to early concern as to the true age of the sequence (Ashworth et al., 1997; Miller, 1996). The youngest date is impossible, as Late Wisconsin ice covered the area at that time and the cluster of 40-42 ka ages were shown by additional dating (Karig and Miller, 2013) to be from reworked material. The most reliable ages, from single, identifiable plant fragments, are in a tight range of 34-35 ka and are interpreted to be the true age of the lacustrine sequence. Both plant and insect fragments indicate an arctic to sub-arctic landscape during varve deposition (Miller, 1996; Ashworth et al., 1997; Ashworth and Willenbring, 1998).

Lacustrine deposits interpreted to be also a part of the mid Wisconsin assemblage are exposed to the west of the area in which the sequence described above occurs but the two are separated by the unit dominated by coarse gravel (Fig. 7). The correlation of the two lacustrine sequences is not straightforward because the lithologies are significantly different and only one radiocarbon age, of a reworked spruce knot, has been obtained from the western sequence (Bloom, 1972). Subsequent to fieldwork for this study, notes and core samples were found in the Schmidt collection at the Paleontological Research Institute (PRI Acc #1486) indicating thin bedded red and gray clay in the second tributary west of Burns Rd (Schmidt site 367-3) and supporting the correlation of these two sequences.

The western lacustrine sequence is dominated by massive to indistinctly bedded pink clay that might be a mixture from the red and gray clay sources. At the southwestern margin of these clay exposures are gravels composed of very angular clasts of the local bedrock that appear to be interbedded with the clay, or locally, thin-bedded silt (Fig. 8B). At least some of these gravels are sourced from a bedrock wall to the northwest that trends about N30°E and appears to mark a tributary to the interglacial gorge that is incised into bedrock. Similar angular-clast gravels, with imbrication showing a northward flow, occur near the northeastern end of the clay exposures and support this canyon interpretation.

Beneath the southwestern-most exposures of this sequence are dark brown current-bedded sands and silts with both sub-rounded and angular clasts of local bedrock. These beds appear to be quite different from the overlying sequence and have a high organic content, in which abundant plant material and some beetle elytra occur, representing a tundra to marginal boreal environment (references in Karig and Miller, 2013). Three radiocarbon ages from the plant material are between 41-43 ka (Karig and Miller, 2013). These strata probably represent deposition in pools within the canyon and, being about 6 ka older than the lacustrine sequence, must be separated from them by a significant disconformity.

About 1/2 mile northwest of the western sequence of lacustrine sediments several more exposures of lacustrine sediments (Plate 1), suspected to be related to these, were later discovered. The first of these exposures, lower in elevation than and to the NE of mid-Wisconsin till in its westernmost exposures (Fig. 6) is a laterally extensive exposure of thin bedded gray clay (Fig. 9). The bedding is apparent only on weathered surfaces because there is no discernible variation in grain size. The bedding apparently reflects differences in consolidation. At the base of one end of this exposure are large, mostly round cobbles to boulders that are clearly imbedded in the clay and around which the clay bedding is draped (Fig. 9). The base of this boulder cluster is below creek level, making
interpretation of the mode of deposition difficult but it was probably not an iceberg dump because there are no clasts smaller than several inches and none of the clasts are striated. The occurrence of clay beneath some boulders argues against their being a substrate. Perhaps they are boulders rolled in from an adjacent shoreline. This clay is overlain by a diamictic till of uncertain, but probable Late Wisconsin age.

About ¼ mile further down the same drainage and close to the bedrock surface of the interglacial gorge is another group of exposures that might also be part of the mid Wisconsin assemblage (Fig. 6). Sparse exposures, several pits and half a dozen auger holes revealed a sequence composed of a basal gravel, an overlying bedded silt and a channel-fill gravel cut into the top of the silt (Fig. 10).

Although reached only in several auger holes, the basal strata consist of several feet of gravel, probably from a stream that flowed down the gorge. Clasts from ¼” to over 1” that were recovered from the top of this gravel unit or from within the silt were round or fractured with high fraction of exotics, mostly limestone (Appendix 2; bag 72).

Overlying this gravel is at least 20’ of very dense light brown silt to very fine sand that shows definite but indistinct and perhaps wavy bedding. The lowermost several feet includes layers or zones of medium grained sand and a moderate number of clasts. Most of these clasts are from granule to 1” in size.

An Optically Stimulated Luminescence (OSL) age of 37,085±3830 yr was obtained from a sample taken approximately in the middle of the silt section. According to the analyst (Steven. L. Foreman, U. of Illinois at Chicago) this sample showed large overdispersion indicating multiple grain populations, so that the most representative depositional age would be the youngest sub-sample. Despite this uncertainty, the silt is clearly not Early Wisconsin in age as originally suspected. If the age were accurate, it would be equivalent to a radiocarbon age of about 32 ka, which would indicate that the silt is of mid Wisconsin age and, with the large possible error range, most likely related to the other mid Wisconsin lacustrine sequences.

Overlying this silt, at least locally, is a unit dominated by cobble- to boulder-sized clasts. The contact is very sharp, with clasts partly embedded in the silt. In the one available exposure this clearly depositional contact dips south but has a channel 2’ across cut into it (Fig. 10). The silt underlying the contact is very fresh and firm with no weathering or discoloration.

The gravel to cobble sized clasts in this overlying unit are mostly round with a large exotic component, dominated by carbonate (Appendix 2; bags 74, 75). At least one red clay clast about 6” long was observed. The unit is matrix supported but is actually a very poorly sorted assemblage of grain sizes, from silt, even clay, to boulders. The boulder-sized clasts appear

Figure 9. Thin bedded clay of unit 1 in the tributary entering below the 60’ dam with boulders embedded by some uncertain process.
to include both round and less round examples and appear to have a higher fraction of local lithologies than pebble-sized clasts. No clast imbrication is apparent.

Slumping on the slopes to the south and east of this exposure obscures stratigraphic relationships but the distribution of the very large clasts indicates that this channel fill is several 10’s of ft thick and extends several hundred yards to the south. A similar zone of large boulders lies west of the tributary and would suggest a linear sediment body that extends at least 100 yards NNW-erly. This deposit appears to represent a sub-aqueous or sub-glacial channel incised into the silt substrate and filled by a very high-energy process such as mass flow.

Figure 10. Cobble channel eroded into silt of unit 1 in the tributary below the 60’ dam. This channel could be a feeder to the sub-aqueous fan.

The gravel unit (lithologic unit 2), consisting of sands and pebble to cobble sized gravels that separates the eastern and western lacustrine sequences, is exposed along the south side of Sixmile Creek from the upper end of the impoundment behind the silt dam downstream at least as far as the upper end of the Ithaca Reservoir (Fig. 6). At its southeastern margin this unit is stratigraphically correlative with the upper part of the eastern lacustrine sequence and overlies lacustrine clay near Burns Rd.

The easternmost exposures of this lithologic unit, in several small gullies south of the silt dam pond (Fig. 6), are dominated by sands and gravels, the clasts of which are mostly granule to pebble sized. Occasional clasts reach 2”. About 40% of the clasts are of exotic origin (Appendix
and are rounder than are the local clasts. Most of these gravels are matrix supported by fine to coarse sand, and are without silt or clay. Some sections, especially the sands, are thin bedded, whereas other sections show only indistinct bedding.

A large exposure of unit 2, west of those described above but still east of Burns Rd, show similar, but significantly coarser gravels (Fig. 8B). Here, a 35’ thick sequence of roughly bedded coarse sand and gravel shows definite coarsening upward to include clasts 4-6” in size at the top. Gravels in this exposure tend to be clast supported, usually with a coarse sand matrix. Exotic clasts, about half the total (Appendix 2; bags 9, 41), are roughly equant and round to sub round, whereas the local clasts tend to be tabular and less round. A rough but distinct bedding indicates a low (±5°) easterly dip, within which the gravel clasts are strongly imbricated (Fig. 8B), showing transport from the west.

Exposures at the base of the tributary just west of Burns Rd display even coarser clasts, with clast-supported cobbles up to at least 10”. Over half the clasts are exotic and round (Appendix 2; bags 5, 47). The more tabular local clasts highlight the strong imbrication showing westward flow. Lithologic unit 2 clearly coarsens westward and probably upward as well. The high percentage of exotic clasts and their easterly or southeasterly transport point to a glacial source. The exposures of this unit are too sparse and scattered to allow definition of its geometry but are sufficient to indicate that it is not a horizontal tabular body. It is quite possible that the extremely coarse channel deposit further west, near the base of the interglacial gorge is part of same unit and represents an even more proximal aspect. Exposures east of Burns Rd are sufficient to show that unit 2 is transgressive easterly over the lacustrine clay of unit 1 (Fig. 7).

These characteristics could best be explained by the origin of unit 2 as a sub-aqueous fan emanating from channels exiting at an ice front. The coarseness of the westernmost gravels would suggest that such an ice front was at or not far from the site of deposition. With an advancing ice front the fan facies should be transgressive southeasterly over the lacustrine clays.

Overlying the western lacustrine clay of unit 1 is a group of lithologies interpreted to be a deformation till (unit 3). Lithologic unit 3 is dominated by sand, usually very coarse-grained, in highly contorted beds, although occasionally the sand is fine-grained. Floating in the sand are “clasts”, often large irregular masses, of silt, red clay and gravel (Fig. 8D). Gravel and cobbles also appear in larger masses, most often as sand-matrix supported diamictons. Both the matrix and the massive sands are very calcareous but show no cementation because a significant fraction of the sand grains are carbonates. Bedding, often with high dips, occurs in some parts of these exposures (Fig. 8D), but in general the bedding is chaotic and the structural pattern is incoherent.

The diamictons have a very large exotic clast fraction, dominated by limestone and dolostone (Appendix 2). The exotic clasts are usually quite round but some have fresh fracture surfaces. On the other hand, many or most of the local clasts are extremely angular. Some larger cobbles show glacial striae. Clasts in these diamictons are very similar in composition to those of the cobble gravels of the lithologic unit 2 (Fig. 8B), but show stratal disruption, clast breakage and glacial striae. It is therefore assumed that the gravels of unit 2 are protoliths for the gravels of lithologic unit 3.

Exposures of these highly deformed sediments are restricted to the NW area of the pre-Late (mid) Wisconsin deposits and extend from elevations not far above those estimated for bedrock up to at least 850’. These deformed sediments overlie the sediments of the western aspect of unit 1 but their stratigraphic relationship to the cobble gravels to the SE is not observed. To the NW the exposures of the deformation till are terminated by a northwesterly drop in elevation of the base of the Late Wisconsin till (Fig. 7), which clearly overlies bedrock about 500 m NW of the area shown in Figure 6. A number of origins for this unit were considered, such as landsliding, soft sediment fluidization and pro-glacial thrusting, before
concluding that it was a deformation till. Regardless of which interpretation is correct, this suite indicates a glacial front that must have been very close.

The preservation of the lacustrine deposits to the southeast of such a till and their only partial homogenization into the till suggest that the ice front stopped here. This suggestion has support in the southeastward upramping of the basal till contact required by the areal distribution of lithologies (Fig. 6). In such a case, the till would have formed a terminal or end moraine, which could explain the local rise in elevation of the base of the Late Wisconsin till that overrode and only partially removed that moraine. The genetic relationship of the till to the subaqueous fan deposits and the interbedding of the fan deposits with the dated pro-glacial lacustrine sediments indicate that the glacial advance into the study area occurred during the Cherrytree stade of the mid Wisconsin sub-stage.

**Other Pre-Late Wisconsin Till Deposits**

Additional sediments beneath the Late Wisconsin till occur within the filled section of the 200' interglacial gorge and also in wells drilled upstream of the 60’ dam. Although little is known about the character of these deposits, they appear to include a large component of fluvial sands and gravels, which serve as local confined aquifers. The suspected fluvial sediments at the base of the filled section of the 200’ gorge, just south of Van Natta’s dam, are younger than that gorge and older than the Late Wisconsin till but no other relationships are currently known.

**Late Wisconsin Till**

The till that overlies these older units in the lower Sixmile Trough, downstream from Banks Rd at least, appears to be part of a single Late Wisconsin unit (Muller, 1957). On the other hand there are clearly multiple Late Wisconsin tills in the Willseyville Trough and in the headwaters of Sixmile Creek. How the tills in these two areas are related will be covered later. The strongest evidence for a single till in the lower Sixmile Trough from this study is that continuous sections of till from bedrock to till top can be mapped near the center of the valley, where fluvial or lacustrine sediments would be expected to separate multiple tills. Neither were any soil horizons observed in the many till exposures on either side of the valley. This single till could be a continuum of Nissouri and Port Bruce tills or only Port Bruce till, if the Nissouri till had been totally eroded away by the younger glacial advance. In this section the till is treated just as Late Wisconsin but this problem will be addressed after presentation of relevant data from other parts of the study area.

This Late Wisconsin till displays several aspects or facies, but all are blue-grey where fresh and orange to light chocolate brown where oxidized or weathered. Almost all facies have a silty clay matrix and are moderately calcareous when unaltered.

The most common facies is a blue-grey silty clay, with a variable but low content of clasts (Fig 11B). This facies is most often massive but in some areas displays bedding, which is often deformed (Fig 11A). Deformed lacustrine sediments are exposed intermittently, as rafts within the till, along the entire length of the Sixmile Trough, in the lower half of the till section and near the trough center.

These exposures of deformed sediments are often quite limited in area but in a few cases are several hundred feet in exposed lateral dimension. One such area, just upstream from and overlying the Mid-Wisconsin varved clays in the Sixmile channel consists of well bedded, moderately folded blue-grey silty clay (Fig 11A). The clay is calcareous and has a variable content of clasts, from granule to cobble size. Clasts are dominantly of local origin, with the remainder being other sediments. Most of these clasts are suspended in the clay matrix but there is at least one large lens of cobble gravel that probably resulted from an iceberg dump. This entire area of bedded clay appears structurally involved with the Late Wisconsin till, which overlies and abuts it.

Another large area of deformed bedded sediment that clearly lies within the till was
Figure 11. Lithologic facies of Late Wisconsin till; A. Unit of steeply dipping, well-bedded silty clay with gravel lens, which is a probable till protolith; B. typical blue-grey massive silty clay facies; C. Diamictic facies with angular blocks of local and exotic origin; D. Diamictic facies with many rounded clasts of exotic origin; E. Highly deformed but well bedded silty clay.
mapped just upstream of German Crossroad along both stream banks. In this exposure laminated, clay-rich strata show high dips and numerous small bedding-shortening shear zones (Fig. 12). Lamination is on a 0.1” scale, with very thin silt to very fine sand partings between silty clay. These sediments appear to represent a lacustrine environment further from the sediment source (distal) than the deformed sediment body downstream. Tarr (Williams et al, 1909) and subsequent workers interpreted these deformed clays as a post-glacial lacustrine deposit, with the sediment deformation being a result of slumping. This interpretation is clearly incorrect for several reasons.

This clay is, as are the other till facies, highly consolidated. Measured wet bulk densities of several samples were 2.2 gr/cm$^3$ with calculated porosities between 32 and 35%, which indicate consolidation stresses much too high for post-glacial lake clay. Moreover, this facies occurs deep within the till and grades laterally and vertically into other till facies. Most deformation of the bedded clay is very ductile, whereas the obvious post-glacial slumping of these highly overconsolidated sediments is in the form of brittle rotational slumping.

A second till facies is a diamicton with a high percentage of angular clasts, many of which are quite large (>1 ft) and a few over 20’ in maximum dimension (Fig. 11C). These clasts are both local and exotic in origin. This facies occurs widely, both within the inner glacial trough and on uplands but the clast content differs with location. Several samples of till clasts from exposures along the creek show high

Figure 12. Raft of deformed lacustrine clay within till along Sixmile Creek above German Crossroad; A. Steeply dipping and thrust-faulted lacustrine clay; B. Close-up of lacustrine clay showing mm-scale laminations and one of many small thrust offsets.
exotic clast contents (Appendix 2), whereas the till on the upland has clasts almost totally of local lithologies.

A variant of this diamicton is a “puddingstone” with varying fraction of matrix-supported pebble to cobble-sized clasts, many of which are round and of exotic origin (Fig 8D). Found within the inner glacial trough, this facies probably represents a mixing of proglacial lacustrine and fluvial sediments. Less common, locally occurring till facies have a silt to sand matrix and round clasts, probably reflecting a fluvial protolith over which the ice locally flowed.

These same facies occur throughout the Sixmile Trough with limited systematics in distribution. Huge bedrock blocks, especially of local origin, tend to occur near the base of the till. Clasts in till on the upper slopes of the Sixmile Trough and on the higher topography in general are angular and almost entirely of local origin. In contrast, till near the center of the trough are usually rich in exotic clasts, with a high carbonate fraction (Appendix 2,bags 28, 54).

Deformation throughout the till appears to be very ductile, with extensive mixing of lithologies. The only evidence of discrete shearing was very small-scale thrusting in the finest-grained deformed lacustrine rafts.

Although ice completely covered this region during the Nissouri stade, the thickness of till deposited in the study area varies widely with respect to location. Till filled the Sixmile Trough in places to as much as 150’ above the bedrock surface of the inner glacial trough (Plate 2, Section D-D’). Only a thin capping (a few to a few 10’s of feet) of till overlies bedrock outside the inner glacial trough. This thin cap is most graphically demonstrated by the many bedrock exposures along the small gullies that traverse the outer glacial trough. Till is quite possibly thicker on the lee slopes of hills than on those facing the ice flow direction as noted by Coates (1966), but there are insufficient local borehole data to substantiate this.

The major protolith for this clay-rich till was most likely lacustrine sediment deposited in the glacial troughs, both during the preceding interstadte and in the proglacial lake formed in front of the advancing ice sheet, with which were mixed fluvial sediments and ice-eroded bedrock. The deformed sediment bodies within the till almost certainly represent this lacustrine protolith. This proglacial lake clay most likely was derived from the Cayuga and/or Sixmile troughs because pre-Devonian shales further north tend to supply red or pink clays (Bloom, 1972).

Post-Till Deposits

There are several types of deposits that locally overlie the till in the Sixmile Trough. These include proglacial sediments between Van Natta’s dam and the 30’ dam, alluvial fans along the valley edges and deposits related to the re-establishment of Sixmile Creek. Despite an initial assumption by the writer and published reports (e.g. Williams et al., 1909, Bloom, in prep) of post-glacial pro-glacial lacustrine sediments overlying the till in much of the Sixmile Trough, no such sediments were recognized during this study above an elevation of about 800’. The surficial reddish colored clay interpreted by Bloom as pro-glacial lacustrine in origin is here interpreted as oxidized clay-rich till. However, downstream of the 60’ dam there is a sequence of what does appear to be proglacial deposits overlying till.

Pro-glacial Lacustrine and Deltaic Deposits

The pro-glacial sediments that lie between Van Natta’s and the 30’ dams form a coarsening upward sequence in all the sub-bodies examined during this study. These sediments are poorly exposed and were examined only to a limited degree in pits dug through the overburden and in augered boreholes. The sub-body just south of Van Natta’s dam was recognized by Rich and Filmer (1915, p. 70 and Fig. 13) as “finely laminated lake clays…. on which lies an undetermined thickness of delta gravel”, but most of this sediment body has since been removed as aggregate.
This sediment body appears to have been deposited on the till surface before significant erosion of the till occurred because contours of the till surface project smoothly under these sediments (Plate 2, Section C-C'). This sediment sequence has a maximum preserved thickness of over 100’ south of the 30’ dam and thins to less than 50’ at the northwesternmost exposure (42° 25’ 55”N, 76° 29’ 11”W).

Although Rich and Filmer (1915) describe the basal strata of this sequence as laminated lake clay, no such lithology was observed in this study. Rather, the basal strata in 4 pits and several auger holes dug along the length of the sediment body were massive or indistinctly bedded fine-grained sand. These strata grade upward to clean medium to coarse sand, again basically unbedded, but the few sampling pits toward the top of the sequence show interbedded sand and pebble to cobble gravel. The uppermost strata and float on the surface suggest that the coarsest material caps the sequence. These sands and gravels seem to have no sedimentary structures, such as clast imbrication, and are poorly sorted. Pebble counts from gravels near the top of the sequence show that local clasts comprise between 65% and 80% of the total (Appendix 2; bags 25, 29, 32, 33, 48), which is intermediate between gravels from the present Sixmile channel (90+) and the glaciofluvial gravels (40-60%).

The gravel clasts in the upper part of the sequence, especially in the upstream remnants, are significantly smaller than those in present Sixmile Creek and imply either that the capacity of the stream that transported them either was relatively low or, more likely, there was no supply of coarser material.

A sample of the fine sand very close to the base of this sediment sequence, taken just west of the Ithaca Water Department settling lagoons near

Figure 13. Photograph of basal sediments in the proglacial sequence in an old quarry near Van Natta’s dam from Filmer (1912). The contact at the waist of the person on the right is probably between the till and the bedded basal sediments.
van Natta’s dam, was dated using the OSL technique as 17,840±890 calendar yrs, which corresponds to a $^{14}$C age of about 14.5 ka. This is as great as the age assumed for the Valley Heads advance and must be viewed with much circumspection. What might be best concluded is that this sequence was deposited rather early in the time interval between the beginning of ice retreat after the Valley heads advance and the time when Cayuga Lake reached its present elevation.

These sediments appear to represent an offlapping sequence that began deposition in a lake whose water level was initially about 780’ and fell relatively rapidly. Such a conclusion assumes that the gravels capping the sequence are shoreline deposits of some sort and that the fall in the lake level is marked by the northwesterly drop in elevation of that cap. The source of these sediments must have been from the southeast to account for the coarsening upward sequence, but the reason for the relatively low local clast fraction and small clast size is unclear. Perhaps the newly re-established Sixmile Creek that was the initial source had a higher content of exotic detritus and smaller clast size than later, when local bedrock became a more dominant source.

Possible outliers of this pro-glacial sequence have significantly different stratigraphies than that of the main body. The upstream outlier at 800’, SW of the City Reservoir, appears to consist of a sheet of unbedded gravel less than 10’ thick overlying till. The grain size ranges from coarse sand to cobbles several inches across but mostly less than 1”. The pebble fraction is dominated by platy, sub-round to sub-angular clasts, 89% of which are of local origin (Appendix 2; bag 84). This clast assemblage more closely resembles that of present Sixmile Creek than that of the main pro-glacial sequence.

The stratigraphy beneath the Clinton St. terrace was documented in 6 hollow-stem auger boreholes with split-spoon cores. The longest of these boreholes was spudded on the terrace top, reached bedrock at 82’ and was personally monitored. The sections in all the boreholes were dominated by sand and gravel, with till recovered in the deepest borehole for a short but poorly determined distance above bedrock. The upper 50’ of section shows stratification and is fairly well sorted, leading to a fluvial interpretation but the deeper strata are poorly sorted and in some cores look diamicitic. A core at 75’ was a very consolidated gray silty clay-matrix diamicton that appeared to be till. The strata between 50’ and 75’ is of indeterminate origin but might be either till or some sort of mass wasting deposit. Pebbles from material at 20’ and 50’ were round to sub-round and about 65% were from local sources (Appendix 2; bags 82, 83) and thus are slightly more glaciogenic than the gravels in the main body of the pro-glacial sediments.

Construction site boreholes in the section of the Ithaca alluvial fan just west of the 200’ gorge show a generally tripartite sequence of sand and gravel over silt and clay with a basal till. The latter two units are not everywhere reported and the elevations of the unit contacts vary widely.

The upper sand and gravel directly underlie the Ithaca fan and can reasonably be identified as fluvial. The clay/silt unit is described as “varved” in several holes and in other holes organic material is reported. A sample examined from a 60’ depth in this unit was a dark gray silty clay with a pinkish cast when disaggregated. The elevation of the contact between this unit and the overlying fluvial sediments is about 390’ in several holes but deeper in others. The known characteristics of this unit indicate that it is a proglacial lacustrine deposit. The varying elevation of the upper contact suggests that the overlying fluvial sediments have eroded channels into the top of the lacustrine unit. A thin basal unit that appears to be till was noted in some but not all boreholes that reached bedrock, a conclusion also reached by Lawson (1977).

Other Post-Glacial Sediments

Other deposits mapped in this study that overly the till in the Sixmile Trough are those of the alluvial fans and gravel-rich caps along the northern edge of the valley floor. The Besemer Hill Rd fan (Plate 1) lies directly on till and
comprises material from pebble to boulder size. In some sections the gravel seems fairly well-sorted, whereas in other places sorting seems absent. Two pebble counts showed that about 90% of clasts were angular to sub-angular and of local derivation, (Appendix 2; bags 13, 14) very similar in content to the alluvium in the present creek (Appendix 2; bag 56). More limited examination of the fan near the intersection of the Brooktondale Rd and State Rte 79 indicates a similar character.

An apron of gravel-rich sediment covers the till along most of the north side of the valley in the Sixmile Trough. This capping ranges from about 1’ to more than 5’ in thickness where examined and there is some indication that it thickens toward the valley edge and toward the fans. A deep pit through this cap west of the more westerly fan, at 42°24’10.7”N,76°25’49.8”W, revealed 6’ of poorly sorted material that lay with a very sharp contact on till (Fig. 14). Clasts range from coarse sand to 4”-5” cobbles, with a clast composition and character identical to those in the fans (Appendix 2; bag 26). The apron could be the distal aspect of the fans, but as or more likely, could represent inwash, perhaps dumped onto the ice and deposited as ablation till, which would explain the lack of sorting.

Alluvial deposits of Sixmile Creek comprise another, albeit minor type of post-glacial deposit. These gravel rich sediments form a thin layer over the till along the present stream channel and also partially cap stream terraces that flank the channel. The thinness of this alluvium reflects progressive post-glacial channel degradation into the till along the Sixmile Trough.

For completeness, the historic lacustrine and fluvial sediments overlying the Sixmile creek alluvium below Van Natta’s dam are mentioned. These underlie a flat-topped stream terrace and represent the fill of a millpond. Early maps of the area show a dam of some sort at 42°26’19.7”N, 76°29’34.9”W shortly after 1800. The large wooden Halsey dam existed at about the same site for at least several decades before 1850 and was destroyed by the flood of 1857 (Selkreg, 1894). These deposits consist of sand and gravel just downstream of the filled section of the 200’ gorge and fine downstream to thin bedded silts and clays with a high organic content near the dam site.

INTEGRATION OF LANDFORMS AND LITHOLOGIES

The oldest glacial landform recognized in the Sixmile Trough is the outer glacial trough. No lithologic units can be associated with this trough and it may represent multiple glaciations. This trough may well be pre-Illinoian. The argument for such an age begins with the assumption that the 600’ gorge is of Sangamon interglacial age (125k-75k yrs bp), as was suggested by Muller
and others, because of its extensive development relative to the post glacial gorges and because it is older than the mid-Wisconsin glaciation. With that assumption, the inner glacial trough, which is clearly older, is quite likely of Illinoian age. The outer glacial trough is older than the inner glacial trough and thus possibly pre-Illinoian.

The till that outcrops upstream of the silt dam beneath the varved clays lies on the floor of the inner glacial trough and is either roughly coeval with or younger than the trough. Both till and trough can be most logically be related to the Illinoian glacial stage. The 600' gorge is cut into floor of the inner glacial trough, on which the older till lies, supporting the interpretation that this till is older than the gorge.

The upper sections of the hourglass tributaries could possibly be the next oldest feature mapped in the Sixmile Trough. Because they are partially filled with Late Wisconsin till they are certainly at least Mid Wisconsin in age. Whether they predate the deposits related to the Cherrytree Stade is uncertain but they could well have developed during the Sangamon period of valley incision.

The deposits of the mid Wisconsin Cherrytree Stade document a southeasterly advancing ice front and an associated pro-glacial lake some 34-37ka radiocarbon years ago. The proglacial lake must have had a water surface elevation of at least 870', at which the highest exposures of lacustrine sediments were noted. This lake would have had to drain southeasterly, out the through valley in the Willseyville Trough, but the elevation and condition of that through valley were probably far different from that developed during the Late Wisconsin.

It is likely that the 200’ gorge was cut during the Plum Point Interstade following the Cherrytree ice advance although no field relationships between that gorge and the Cherrytree deposits were observed.

The major advance during the Late Wisconsin must have been associated with a pro-glacial lake, as documented by the rafts of lacustrine strata within the Late Wisconsin till. These lacustrine sediments appear to have been a major protolith for all facies of that till. Although the total extent of this lake is unknown, it must have occupied much of the Cayuga Trough and all the Sixmile-Willseyville Trough at its maximum. It would have shrunk in areal extent as the ice front moved south and disappeared as the ice passed through the drainage divide at the through valley.

Whether the ice front retreated north of the Sixmile Trough during the Erie Interstade will be discussed later but the direction of ice movement clearly changed during the Late Wisconsin. Striae south of where ice reached during the Port Bruce Stade indicate a west to southwesterly flow during the Nissouri advance (Williams et al., 1909), whereas the striae and megaflutes in the areas covered by Port Bruce ice indicate a south-southeasterly flow at that time (Fig. 3 and Williams et al., 1909).

The channel north of and parallel to the present creek just upstream of Burns Rd is difficult to explain as a fluvial channel because of the lack of fluvial deposits within it and because the elevation at its lower end is well below the top of the post-glacial pro-glacial sediment body downstream. This condition would imply that the channel was active well after the fluvial deposition of coarse clastics downstream without itself having a gravel bed, an unlikely situation. A clue to a possible origin may be that this channel lies within a linear sag in the till surface and might be related to that sag. That suggests that the channel might have been a sub-glacial Nye channel. With such an origin, flow could have been in either direction, depending on the hydraulic gradient within the ice.

No evidence was found for the proglacial lake with a surface elevation of 980’ that has been commonly proposed. At elevations above about 800’ the till is locally overlain by inwash and alluvial fans.

The highest lake level, as indicated by the pro-glacial sediment sequence is about 780’. These sediments appear to represent an offlapping sequence in a lake whose water level was initially about 780’ and fell relatively rapidly. Moreover, the fine-grained basal strata and coarsening
upward sequence implies the lake formed during a rapid inundation of the valley rather than behind a retreating ice front, in which case coarse basal strata would be expected (e.g. Randall, 2001).

How the Clinton St. terrace, the sediment fill of the 200’ gorge and the Ithaca fan relate to each other and to the pro-glacial sediments described above is not obvious. In the upstream section of the 200’ gorge late Wisconsin till overlies fluvial sediments but in the section buried beneath the Ithaca fan this till, when present, is the basal Quaternary unit. The thinness or lack of till beneath the lacustrine sediments in boreholes on the Ithaca fan suggest a period of erosion preceding the existence of a pro-glacial lake in this area.

This downstream till is overlain in most boreholes by pro-glacial lacustrine sediments that require a lake level that was at least 390’ and, because these sediments are an offshore facies, was probably significantly higher. It is quite probable that they were contemporaneous with some of the pro-glacial sediments mapped above Van Natta’s dam, which would represent their nearshore equivalent.

Creation of the Clinton St. terrace is not easily placed in the sequence of events described above. It is fluvial in origin and post-till in age but the terrace surface lies above the fan surface on which Ithaca lies. It might be a remnant of an older fan at that level but it is more likely a kame terrace adjacent to the ice front that blocked the lake in the Sixmile valley.

WILLSEYVILLE TROUGH

The Willseyville Trough has undergone relatively little stream erosion since ice withdrawal, which has led to the preservation of a wide range of glacial landforms. In addition to the kames and outwash associated with the Valley Heads moraine there are ice marginal channels, a large delta and a glacial lake outlet channel.

LANDFORMS

Glacial Trough

The Sixmile-Willseyville Trough narrows and the valley walls steepen southward into the Willseyville Trough section. The Willseyville Trough is quite linear and is associated with prominently truncated spurs, demonstrating intense glacial erosion.

This section of the Trough cannot easily be separated into inner and outer glacial troughs, in part because subsurface data are too sparse. The only site with reasonable seismic control is at Ridgeway Rd (Plate 3, and Fig. 7 of Miller and Karig, 2010). Along this seismic section, the trough displays subsurface benches on both sides near an elevation of 775’ (Plate 4, Section G-G’). On the axial profile of the Sixmile-Willseyville Trough (Fig. 2) this elevation could be correlated with the base of the inner glacial trough in the Sixmile Trough section. The elevation of the deepest point on the seismic section (680’) lies along the extrapolated gradient of the 600’ interglacial gorge, but more data are needed to substantiate this extrapolation.

If the benches mark the floor of the inner glacial trough, its extrapolation to the center of the valley shows that the trough floor rises gently southward to the vicinity of Ridgeway Rd, but appears to deepen again southward from that point (Fig. 2), based on a refraction profile (Miller and Karig, 2010) located near the center of the valley just northwest of the junction of Coddington and White Church roads (Plate 3 and Plate 4, Section F-F’).

It is approximately here that the trough crosses the pre-glacial watershed boundary and has created a classic through valley where ice erosion massively degraded a pre-existing drainage divide. Here the glacial trough is narrow, with a classically U-shaped section, and is bounded by the highest hills in the area. Although the floor of the glacial trough has a maximum elevation of about 775’ in this same area (Fig. 2), the bedrock divide is very subtle. The present drainage divide is roughly coincident with the bedrock divide, but the highest elevation
of the valley floor lies several miles to the south, on the outwash plain of the Valley Heads moraine.

**Valley Heads Moraine and Outwash Plain**

The Valley Heads moraine is a system of moraines extensively developed in central New York during the Port Bruce Stade. Although present in all the through valleys and many other larger valleys of the Cayuga region, these moraines are seldom traceable across the interfluves. In the Willseyville Trough there is no morphologic expression of a Valley Heads end moraine. Instead, the associated outwash plain is bounded to the north by a steep north-facing slope that represents an outwash head (Plate 3). This slope marks an ice front that was relatively stationary for some time, most probably due to ice stagnation. It is possible, if not likely, that one or more morphologic end moraines are buried within the outwash. The Valley Heads outwash plain heads on the western side of the Willseyville Trough at an elevation of about 1040’ and at about 1020’ on the eastern side, with southerly slopes on both sides converging and flattening gently southward toward Willseyville. On both sides of the valley the outwash plain appears to be continuous to the north with kame terraces that are most likely parts of the same drainage system.

**Kettle-Kame Terrain**

The valley floor north of the outwash head is an area of irregular topography that extends about to Caroline Depot Rd (Plate 3) and that was termed a kame moraine by Muller and Cadwell (1986) and others. This area is typified by local relief of 10’ to 30’ with abundant local depressions, some of which are water filled. In most of this area there seems to be no pattern to the topography but south of Ridgeway Road the Lidar hillshade imagery (Fig. 15) shows at least two irregular ridges trending perpendicular to the valley axis. Depressions immediately north of the outwash head are clearly kettles and the crudely equant shape of most of the others suggests that they also are kettles. There appear to be concentrations of these depressions both immediately behind the outwash head and near the north end of the terrain, south of Caroline Depot Rd.

Kame terraces, showing varying degrees of preservation, flank the valley on both sides, but are better developed on the east (Fig. 15). The terraces on both sides have a gentle southward slope, implying drainage in that direction. In the center of the valley the kame moraine topography is truncated by the smoother topography of the Willseyville channel, described below.

**Willseyville Channel**

The outwash plain and kame moraine terrain are incised by a prominent channel, here termed the Willseyville channel (Plate 3). This feature is the outlet channel from a lake to the north and is presently occupied by a nearly continuous chain of wetlands.

The southern section of this channel, where it is incised some 50’ into the outwash plain, is an impressive feature, with steep sides and a flat floor about 700’ wide. South of about 42° 18’ N, where the outwash plain transitions to a valley train, the channel widens, becomes braided and is no longer incised.

North of the outwash head the channel lies within the kame moraine terrain and shows much less incision. This northern section of the channel, as delineated by Lidar imagery (Fig. 15), is 600-700’ wide but the channel margins are less linear, due both to intersection with kettles and to the intrusion of alluvial fans from side streams entering the Willseyville Trough. The largest of these fans enter from the west near Belle School Rd and form the drainage divide between Willseyville Creek, flowing south into the Susquehanna system, and Beaver Brook flowing north into Sixmile Creek. Wetlands that appear to mark the continuation of the Willseyville channel continue northward almost to Caroline Depot Rd. In planform this channel shows a sinuosity with a wavelength of about 10,000’.
Figure 15. Lidar hillshade image of the Willseyville Trough between Ridgeway Rd and the junction of Coddington and White Chruch Rds, showing the kettle-kame terrain cut by the Willseyville channel. The kame terraces are better delineated by Lidar topography than by hillshade. Only the most obvious kettle and depressions are denoted. The transverse ridges probably mark thrusts of ice caused by minor re-advances.
Brooktondale Delta and Adjacent Area

In the area where upper Sixmile valley and the Willseyville Trough meet to form the lower Sixmile valley is the large Brooktondale delta (Plates 1 and 3) described by Tarr (Williams et al., 1909, p. 185). This delta clearly demands a body of standing water but the size and significance of this water body is contentious. The delta has a planar top that slopes gently westward from about 1030’ to no less than 1010’, based on contours on the USGS 1:24000 quadrangle, generated before gravel mining removed most of the delta. The contact between the topset and foreset beds, which marks an elevation just slightly less than the associated lake surface, is estimated from photographs and Lidar 2’ contours as about 1000’ on the eastern quarry wall.

The shape and internal structure of the delta shows that it was sourced from the east. An arcuate delta front is probably preserved in the topography along the eastern side of the Beaver Creek valley, especially upstream of where that stream is more deeply entrenched.

Sixmile Creek has incised a deep valley into the north side the delta, which was thought by Tarr (Williams et al., 1909), Miller (2009) and others to have extended north of the creek as a broad flat area at 1020’ to 1030’. However, during this study no evidence of deltaic sediments was found north of Beaver Brook Rd, where only glaciofluvial sediments and tills were observed.

Figure 16. Lidar topography of the area around Brooktondale as marked on Plate 1. Shown here are the high-level fluvial terraces marking the first surficial post-glacial flow down the Sixmile Trough. Also shown is the moraine marking the post-Valley Heads (Brooktondale) ice advance (red) and a channel that possible fed flow under the ice.
North of the delta are two fairly flat surfaces; a higher one with an elevation of 1020-1040’, which exists only north of Sixmile Creek, and the second at about 940-950’, which occurs both north and south of the creek (Plate 3, Fig. 16). The boundary between two surfaces north of the creek is a smooth arcuate slope that may represent an ice contact surface.

At the south end of the lower surface just north of Beaver Brook Road is a topographic high, now almost totally removed but which has an east-west trend on the 1969 USGS 1:24000 Ithaca East topographic quadrangle (Plate 3), made before quarrying extended to that area. It is quite likely that this is a moraine of some sort, as will be later amplified. The surface north of this postulated moraine is shown by the 2’ contours of the Lidar map to consist of a series of terraces separated by low-amplitude arcuate meander scrolls (Fig. 16). The highest of these terraces, at 960’, represents the earliest unambiguous evidence of northwesterly post-glacial drainage of Sixmile Creek.

The top of the higher surface is cut by a flat-bottomed channel about 250’ wide that trends NNW along Van Demark Rd to its junction with Landon Rd, where the channel turns west and becomes a steep gully that debouches on the lower surface (Fig. 16). The steeper, gully section of the larger channel is also flat-floored. The head of this channel, at an elevation of 1020’, is truncated by the Sixmile valley, which clearly postdates the channel. There is neither any sign of this channel on the south side of the valley nor is there an alluvial fan where this channel flattens onto the lower surface as would be expected of a typical surface stream.

East of this channel the upper surface is covered by several small hills underlain by sand and gravel and further to the east is a low, discontinuous ridge that trends N-S (Plate 3, Fig. 16). Both these features are interpreted as morainal.

Lateral Moraines and Channels

Features in the Wilseyville Trough that are either ice marginal channels or lateral moraines, or both, are recognized near the northwest corner of Bald Hill and also east of the Valley Heads ice front. These features, which have been described by Tarr (Williams et al, 1909) and Rich (1908), are expressed as channels or terraces that roughly follow the hillside contours. They often begin indistinctly and end suddenly at gullies that extend downslope.

Most or all of the marginal channels observed during this study appear to have been trapped upslope of lateral moraines, which are composed of relatively impermeable clay-rich till. These channels were probably created by streams fed by ice melt and upslope drainage that flowed along the moraine until, reaching a place where the moraine was an insufficient barrier, plunged beneath the ice in subglacial chutes. These channels would perhaps be better termed marginal meltwater channels than ice marginal channels (Benn and Evans, 2010).

Just south of Brooktondale and along the northwest corner of the Bald Hill massif is a series of such abandoned marginal channels (Plate 3). The highest and most southerly, beginning at an elevation above 1230’ is also the least well preserved. This channel is bounded on the east by the steep bedrock valley slope but on the west by morainal till. Subsequent gully erosion has removed some of this channel and downslope mass movement has obscured other sections but it is clear that the channel slopes southward and may actually consist of several levels. This channel disappears to the north along the valley slope, but can be followed for at least 1200’. To the south it curves sharply westward, dropping downhill, and probably becomes a sub-glacial chute.

The next channel to the north lies near the base of the valley slope at an elevation of about 1050’ and appears to debouch onto the kame terrace along the east side of the valley (Plate 3). The upper end of this channel projects into the largest and most extensively traced of these channels, which is undoubtedly the one recognized by Tarr (Williams, et al., 1909, p.157).

This large channel can be traced from the south flank of upper Sixmile valley at an elevation of
1080’, westward around the corner of Bald Hill into the east flank of the Willseyville trough and also debouches into the area of the kame terrace (Plate 3, Fig. 17). The channel has a broad flat floor where not filled by younger sediment and is bounded by the steep bedrock valley slope on the south and east. The western flank consists of a till moraine along most of its length, but bedrock is exposed in several places beneath the till, indicating that the channel was forced to cut downward into bedrock of the valley slope.

Several other channels can be identified to the north and/or west of the large marginal meltwater channel and at lower elevations (Plate 3, Fig. 17). As clearly shown in the field and by Lidar topography, the uppermost two channels merge at their lower ends and continue as a single channel that curves westward and then northward into the area of the delta. Evidence from this deltaic area has been removed by aggregate mining but this channel is clearly seen as a N-S trending depression across the delta on aerial photos flown in 1936 (Fig. 17) and on topographic maps generated before significant mining occurred. This channel system develops near an elevation of 1030’ and becomes a pronounced gully as it drops to an elevation near 980’, where it swings north, flattens and broadens as it cuts through deltaic deposits at an elevation of about 960’.

There are several unusual aspects of this channel system. The planform geometry of the channel system, with its 180° change in direction, as well as its sudden initiation on the hill slope would identify it as a glaciogenic feature. This would explain the ability of the channel to flow through the high-standing delta rather than southward where elevations were lower. The most plausible interpretation is that the two,
almost concentric forks of the system represent channels marginal to an ice lobe. To cut across the delta, this channel must have been initially above the delta top at 1020’ or higher and then cut its way downward. It thus must have started as a supra-glacial or englacial feature but clearly became sub-glacial and flowed north into the remaining ice mass. This interpretation and the problems it creates will be discussed later.

Two other channels trend west-southwest on the large terrace east of the delta (Plate 3, Fig. 17) at an elevation of about 1010-30’ and lie north and east of the system described above. These channels are in a location and at elevations to identify them as fluvial feeders to the delta. In that case they must be older than the arcuate channel system that cuts through the delta but younger than the higher ice margin channels. Both these channels show subdued relief, suggesting modification by post-Valley Heads ice.

On the east side of the Willseyville Trough above the Valley Heads outwash head is another well-defined marginal channel (Plate 3). This channel starts as a slope break near 1160’ and southward becomes a better defined channel carrying a small stream, along which till is exposed in few places. The channel ends at its south end in two steep gullies that trend westerly toward the floor of the Willseyville channel and are most probably sub-glacial chutes. What appears to be another marginal channel trends southerly along the kame terrace at 1020’ and drains into one of the chutes (Plate 3).

LITHOLOGIES

Most of the lithologic data from the Willseyville Trough, which are limited by the relative lack of post-glacial erosion, are from well data and from exposures created by aggregate mining. Moreover, many of the well data are of questionable reliability and provide no information concerning sedimentary structure, which makes determination of depositional environment difficult. In addition, there are no wells that penetrate the thick valley fill south of the Brooktondale delta. For all these reasons, interpretation of the stratigraphy and depositional history in the Willseyville Trough is much more tentative than that of the Sixmile Trough. Lithologies are thus described more by area than by age.

Outwash Plain

The sediments of the Valley Heads outwash plain are best exposed in an aggregate quarry about 0.4 mile south of the outwash head (Plate 3). About 70’ of roughly bedded sand and gravel, with clast size mostly less than 6” are exposed in the quarry walls. The total thickness of the outwash is unknown but southward extrapolation of the till north of the ice margin toward the quarry and hearsay drillhole information would suggest that it is not much more than about 80’.

In the lower section of the outwash the clast composition is about 50% exotic, with a high (>30%) carbonate component (Appendix 2; bags 55,64,76,77). Near the top of the outwash the exotic component of clasts drops to about 25% and the carbonate component drops to about 15% (Appendix 2; bags 62,63,65). Exotic clasts are more equant and rounder than the local clasts. These characteristics indicate a transition from a primarily glaciogenic source to sources dominated by local lithologies.

At a depth of about 30’ along the east side of the quarry is a zone of mixed and unsorted material with a few angular blocks well over 4’in size within a silty clay matrix that appears to be a deformation till. The large blocks are non-calcareous siltstone but contain numerous brachiopod and molluscan fossils. By 2011 excavation had exposed a clay-rich, matrix-supported diamicton on the north wall at a depth of about 40’ (Fig. 18). This diamicton clearly displays red-brown oxidized outer layers bounding an unaltered, blue-grey central section and is interpreted as a till very similar in character to the Late Wisconsin till in the Sixmile Trough. Both tills in the quarry demonstrate that the ice front oscillated during Valley Heads advance.
Kettle-Kame Terrain

The two seismic profiles run in the kame moraine terrain of the Willseyville Trough (Miller and Karig, 2010) reveal up to 300’ of valley fill, but there is no lithologic information about any but the shallowest of these deposits and about those near the edge of the valley. Extrapolating from the somewhat better controlled stratigraphy around the delta, these deeper deposits are likely to include a number of tills as well as other glaciogenic sediments.

Surficial deposits appear to be mostly thin kame sands and gravels that overlie till. Kame deposits are clearly exposed in several excavations near 42°19’07”N, 76°22’30”W. Most wells along the valley edge penetrated surficial till or, at lower elevations, till capped by coarse sand and gravel up to several tens of feet thick, probably representing kame deposits. Well TM 42 (Plate 3) penetrated 22’ of silt beneath kame deposits, which could represent a local glacial lake or a southern section of the lake into which the delta was deposited. Several wells along the west side of valley penetrated a layer of sand and gravel between tills or within the surficial till. Till was recovered from a shot hole at an elevation of 970’ along the refraction line just north of the outwash head (Plate 3, Fig. 15), suggesting that the kame deposits are quite thin.

A pit dug into one of the transverse ridges in the kettle-kame terrain (Site 85, Fig.15) revealed a silt matrix diamicton, with clasts ranging in size
to over 1’, some clearly striated. Approximately 80% of the clasts are of local origin, and both local and exotic ranged from round to angular (Appendix 2; bag 85). These characteristics lead to an interpretation of these ridges as till moraines, probably created by thrusting of active ice over the stagnant ice masses to the south. In a more typical kame (Site 88, Fig. 15) another pit revealed clast-supported pebble to cobble gravel. Although no sedimentary structures were discernable, the exposure appeared fluvial. The clasts were 90% local lithologies and mostly round to sub-round (Appendix 2; bag 88). However, a sample from another nearby kame (Site 93, Fig. 15) had an unusual array of clasts. Over 20% of the clasts were exotic (Appendix 2, bag 93) and include soft red mudstone in addition to a variety of sandstones and carbonates. In contrast, a sample from the kame terrace to the east (Site 92, Fig. 15) was dominated by angular clasts of local lithologies (Appendix 2, bag 92).

Two closely spaced core holes (AB-1 and AB-2) in the kettle closest to the outwash head (Plate 3) penetrated about 16’ of peat, which overlay organic rich lacustrine sediments, and bottomed in cobbles at 18’ in the auger hole (AB-2). The sub-peat sediment showed banded dark gray to black layers (gyttja) in a Russian peat core hole (AB-1) and gray-green clay with a few gastropods in the auger core. In both holes this clay had numerous plant fragments, including twigs and a black spruce cone (Dorothy Peteet, personal communication, 2012). Four radiocarbon ages were obtained from the basal sediment. The two from the Russian peat corer at 16’ and 17’ were from bulk organic samples and gave ages of 12.1 ka and 12.3 ka respectively (Appendix 1). Two samples from 17’ in the auger core hole (AB-2), were from macroscopic spruce and other plant fragments and both gave ages of 11.7 ka. The greater ages from bulk samples are almost surely due to old carbon and the true radiocarbon age of this bog base is 11.7 ka.

Willseyville Channel
A series of hand-driven auger holes along the wetlands of the Willseyville channel (Plate 3, Fig. 19), recovered peat and clay, often organic, and bottomed in impenetrable cobbles. These cobbles were at a depth of 2’ to 5’ at the southern part of the cored series but became progressively deeper north of hole R-6, between Ridgeway and Belle School roads (Fig. 19). Peat or peaty clay comprises the upper several feet in most holes, with silty clay dominating the deeper sections.

This clay has a variable content of plant fragments, both aquatic and terrigenous, as well as invertebrates in holes R-7 and to the north. Aquatic plants recognized include sphagnum leaves and charophyte oogonia. Between 4’ and 10’ in hole PR-1 were many fragments and some entire tests of both gastropods (Valvata tricarinata, Helisoma anceps, Gyraulus deflectus) and pelecypods (Pisidium compressum and at least two other species), as well as tubes of rotifers, family Flosculariidae (David C. Campbell, 2012, personal communication). Fewer, but similar invertebrates were observed in hole PR-3, indicating fairly permanent shallow water with macrophytes and terrigenous plant debris in this area. Radiocarbon ages of 11.7 ka from 11.7’ in BS-1 and 12.3 ka from 15’ in PR-3 were obtained from terrigenous plant macrophytes (Appendix 1).

In some holes (e.g. R-7) the contact between the clay and the cobble base was quite sharp whereas in others (BS-1 and PR-1) a transitional zone of sand or sandy gravel overlies the cobbles. Hole BS-1 was at the northern margin of the large alluvial fan that extends across the channel. In hole PR-3 there were zones of pebble-to-cobble-sized clasts between 3’ and 8’ and pebbles scattered through the clay section below but no cobble base was encountered to the maximum 20’ depth penetrated. The occurrence of pebbles within the clay in the northernmost hole (PR-3) suggests an ice-rafted origin, but not necessarily from a glacial source. A more likely source is inwash onto a winter ice cover.

Most clasts in all holes were of local derivation and varied from sub-round to sub-angular. The basal cobble is interpreted to represent the fluvial substrate of the channel, although in some places it could represent fans. In either case, the
overflow (outlet) elevation of lake from which the channel drained could not have been above 967', the cobble elevation in R-6. The existence of the channel north of this sill could be explained by high velocity channelized flow in a shallow pond upstream of the sill.

**Brooktondale Delta Area**

Excavations and boreholes in the area of the Brooktondale delta provide substantial information about the upper part of the stratigraphic section in that area but less about the deeper section. Aggregate mining has removed much or most of the delta but has revealed its internal structure and composition along both the eastern and western margins.

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*Figure 19. Longitudinal shallow geological profile along the Willseyville channel based on auger cores and two water wells. The red profile marks the thalweg within the channel and the blue profile is an interpretation of the channel floor, assuming that it is marked by the cobble layer that prevented further auger penetration. With that assumption, the overflow elevation would be 967'.*

*Figure 20. View of part of the east face of the quarry in the Brooktondale delta showing 2 of the 3 exposed series of foreset beds that mark a progressively northward migration of the delta-feeder channel.*
The earlier phases of delta construction are exhibited along the eastern quarry wall, but how much further east the delta continues is unknown. Shallow bedrock in water wells constrains the delta to areas west of Bald Hill Rd. Most of the eastern high wall is comprised of foresets that are capped by topset beds (Fig 20). The foresets have conical traces on this wall showing at least 3 sediment sources from the east that migrated northward with time. The apparent upward migration of foresets is attributed to the westward migration of the delta front. Foresets at the northeast corner of the quarry dip south, which show that the delta continued for some distance north, into the area of the Sixmile valley, but there is no evidence that the delta existed north of the valley.

The foresets are dominantly coarse sand and gravel with most clasts less than a few inches in size. About 80% of the clasts in these gravels consist of local lithologies (Appendix 2; bags 16, 17), indicating a major source in the upper Sixmile drainage.

Within these foresets, a few hundred feet west of the quarry wall and conformable with the foreset bedding, is a till unit 3’ to 6’ thick (Fig. 21A). This till is composed of silty clay with a minor clast content. Although this till is mostly orange-brown in color, in thicker exposures its center is blue-grey, indicating that the margins of the till have been oxidized, similar to the thicker till exposed within the outwash (Fig. 18). The till has sharp contacts with foreset beds below and above, although one exposure displays an overlying debrite that has caused involution of the till (Fig. 21A).

Along the southern end of the eastern quarry rim the foreset assemblage is overlain by a unit comprised of clasts ranging to several feet in size. Most of these larger clasts are tabular, angular and of local derivation. This unit is several tens of feet thick and seems to coarsen upward. This unit could either represent topset beds or a till, or both.

The material removed from most of the quarry is presumed to have consisted primarily of foreset sediments because these have the desired range of clast size. In support of this conclusion are scattered exposures of foresets remaining along the western rim of the quarry. The best exposed of these are sand-dominated, with southwest dipping beds (Fig. 21B). Along much of the western rim and overlying the foresets are exposures of a clast-rich diamicton. The interpretation of this diamicton as till is supported by the report of striated and faceted cobbles in sediment overlying the deltaic sequence (Bloom, 1972).

Exposures on the quarry floor, at least over most of its southern half, are of flat-lying well-bedded fine-grained sediments (Fig. 21C). Most beds vary from fine to coarse-grained sand, with a few cobbles floating in the coarser beds. A few beds are even finer grained silt and clay. Current bedding is common, showing flow to the south and west. These appear to be bottomset beds, deposited in a lacustrine environment with enough current energy to have flushed most of the clay.

All these bottomset strata lie at elevations of about 950’ or lower. A well (TM 2367), located near the south end of the quarry and spudded at about 975’, penetrated 25’ of sand and gravel, below which was 45’ of silty sand, assumed to be correlative with the exposed lacustrine strata (Plate 1, Fig. 22). Similar sand-dominated sediments are exposed just west of the Beaver Creek Rd bridge at about the same elevation.

No foresets were exposed in the quarry north of Beaver Creek Rd. Instead, the beds at the same range of elevations as the foresets are sands and gravels that appear to be fluvial and/or lacustrine in origin (Fig. 21D). The lower part of this section has a high percentage of exotic clasts, dominated by carbonates (Appendix 2; bag 61), which would indicate a glacial source rather than the local uplands. The clast composition in the upper part of this fluvial section is 80% local with no carbonate (Appendix 2; bag 22). These sediments are interbedded with thin, clay-rich diamictons, similar to the till within the foresets near the east side of the quarry. These thin units are possibly flow tills but still indicate nearby ice.
The flat surface north of the quarried area and between Beaver Brook and Sixmile Creek at an elevation of 960-980’ is capped with very coarse sediment, from cobble to small boulder size. Because this surface is composed of multiple meander scrolls and terraces (Fig. 16), this coarse sediment is composed of various materials layered in distinct strata. Understanding these stratigraphic aspects is crucial for interpreting the geological history and depositional processes of the area. Figure 21 provides visual representations of these stratigraphic aspects, focusing on the Brooktondale delta, with images A to D illustrating different layers and compositions within the quarry. These images highlight the diversity of sediment types, from sandy deposits to clay units, providing insights into the environmental conditions and sedimentary processes during the deposition of these strata.
surficial material is interpreted as a thin fluvial deposit reworked from till. The sediment sequence penetrated in two gravel exploration wells (USG 1&2; Plate 1) drilled on this surface penetrated a sequence of fluvial over lacustrine strata. The slope below the western side of this surface, leading to Beaver Brook, exposes the same lacustrine sand, which generally fines downward and overlies a till in the creek bottom.

This till is exposed along Beaver Brook from Beaver Creek Rd downstream to well TM 1503, (Fig. 22) with an exotic-rich clast composition (Appendix 2; bag 60). This till correlates with the single Late Wisconsin till to the northwest and with the Valley Heads till, which is close to the surface, to the south (Plate 4; Section H-H’).

The Valley Heads till is itself underlain by a section dominated by fine sand that is characterized by upward flowage in drill holes when penetrated. This fine sand appears to represent a fairly low energy environment, here interpreted to be lacustrine. This fine sand unit extends northwestward at least to well TM2355 (Fig. 22), but is not present in wells or in exposures along German Crossroad, where only a single Late Wisconsin till is present. Below the fine lacustrine sands and clay in wells TM 1503 and TM 2717 is a section that appears to be another till but in both wells this section seems to have been deposited within the interglacial gorge.

In summary, at German Crossroad and further northwest there is a single till that reaches a thickness of nearly 150’ (Plate 2, Section E-E’), whereas the combined well logs and surface exposures just north of the delta show three major tills, separated by two lacustrine sequences. The upper lacustrine sequence was deposited in the lake associated with the delta, but the sequence below the Valley Heads till would seem to have been deposited in an Erie Interstade lake and to be underlain by Nissouri till.

The sedimentary sequence beneath the 1020-1040’ surface north of the delta and Sixmile Creek is exposed along the tributary that enters the creek in Brooktondale and also along the

Figure 22. Longitudinal geological section along the junction area of the Sixmile and Wilseyville troughs based on surface exposures and well logs (See Plate 1 for location). The German Crossroad section represents the single till character further NW in the Sixmile trough. This section shows two lacustrine sections in the SE but none at the NW end of the section.
railroad cut just north of the old trestle site (Fig. 16). This area extends eastward beyond the flank of the Sixmile-Willseyville Trough but is discussed here because it is more closely related to the geology around the delta than to upper Sixmile Creek. The deposits exposed in this area include a complexly interbedded sequence of tills and ice-contact fluvial and lacustrine sediments capped by a surficial till and locally overlying sand and gravel (Section I-I', Plate 4). The basal sand and gravel may represent fluvial deposits in the bedrock valley revealed by seismic refraction (Miller, 2009). Clasts in most of the ice contact gravels and tills are fairly exotic-rich, with high carbonate fractions (Appendix 2; bags 49, 50, 51,52, 53), indicating a dominantly glacial source. This ice-contact sequence seems to represent an ice front that oscillated across the area probably during and just after the formation of the delta. Overlying this sequence is a surficial sheet and morainal assemblage of sands, gravels and boulders marking a final re-advance over the area.

INTEGRATION OF LANDFORMS AND LITHOLOGIES

The glacial geology of the area where the Sixmile Trough meets the Willseyville Trough and upper Sixmile valley is complex but even the incomplete interpretation developed here clarifies some critical aspects of the glacial history of the entire watershed.

The till that is found on the higher slopes of the Willseyville Trough, at least south of Bald Mt. (Plate 3) is attributed to the Nissouri Stade because no subsequent ice reached those elevations. This till is a clay-rich diamicton with angular clasts consisting almost completely of local lithologies. Nissouri till is assumed to exist in most of the Willseyville Trough beneath Erie and Port Bruce deposits and it is quite possible that even older Quaternary deposits occur at depth.

The lacustrine sand at the base of several wells (e.g. TM 2367) or that overlies the basal till in others wells (TM 1503, TM 2717) is interpreted to represent deposition in a pro-glacial lake during the Erie Interstade but it is not obvious whether or not these lacustrine sediments once extended further northwest and were removed by Port Bruce glacial erosion. The answer depends on whether the single till in most of the Sixmile Trough represents a continuum of deposition from Nissouri to Port Bruce stades or is only a Port Bruce till, the earlier till having been totally removed by glacial erosion.

Some evidence is offered by the rafts of deformed lacustrine clay within the lower part of the till section in the Sixmile Trough. These clearly represent a more distal lacustrine facies than does the sand deposited in the lake below the Valley Heads till near the delta. Because the ice front was to the northwest these two facies could not have been deposited in the same lake. The simplest solution is that the deformed masses lie within Nissouri till and that there was continuous till deposition in the trough from German Crossroad northwesterly. In that case the fine sands were deposited in an Erie Interstade proglacial lake that did not extend as far as German Crossroad.

The ice advance during the Port Bruce Stade is marked in the southeastern end of the Sixmile Trough and the Willseyville Trough by the Valley Heads till, exposed along Beaver Brook and penetrated near the surface in wells TM 1503 and TM2717 and which is easily correlated with the thick till in wells TM 1808 and TM 2367 (Fig. 22). The lack of deep wells further south prevents a detailed interpretation, but it is apparent from multiple tills in the gravel pit within the outwash plain that the Pt. Bruce ice front oscillated in a complex manner and at times extended well past the Valley Heads outwash head. Gravels in the deeper levels of the outwash and associated with those tills are rich in exotic clasts, the source for which is not obvious. This problem is discussed further in the section on the evolution of the watershed.

The outwash head marks a relatively fixed Valley Heads ice front position, here interpreted to represent a period of glacial stagnation. There
is no evidence of progressive ice retreat, such as outwash bands or recessional moraines. Neither is there any evidence of a proglacial lake immediately north of the outwash head. Lack of such a lake is probably due to the very low relief in this section of the Willseyville Trough, with elevation at the outwash head only a few 10’s of feet higher than at the north end of the Trough. With this condition the hydraulic surface would have been within the ice and drainage probably largely englacial or sub-glacial because surface flow is largely absent in stagnating zones (e.g. Gustavson and Boothroyd, 1987).

At the beginning of this period of stagnation the ice would have covered all the topography bordering the Sixmile Trough and some of the upper Sixmile watershed (Fig. 23). Any debris inwash to the ice would have had to come from uplands adjacent to Willseyville Trough and concentrated near the ice front. The lack of a significant debris cover on the ice significantly north of the ice front would explain the lack of lateral moraines except near the outwash head.

With an insulating debris cover near the ice front, surface melting would have been greatest at the north end of the trough and the ice surface gradient would have decreased during this stagnation period (see Gustavson and Boothroyd, 1987). The high local clast fraction in the upper section of the outwash plain and the continuity between kame terraces and outwash plain indicates that, early in the stagnation period, much or most of the sediment from the uplands was transported along these kame terraces. As the ice surface fell, the sediment probably entered the stagnation zone as inwash, some of which was deposited englacially or subglacially. Inwash, which supplied material for the kames, must have been relatively limited because the kames are only several tens of feet thick.

The several till ridges transverse to the Trough indicate a departure from this general stagnation model. Given the large fraction of local lithologies in these tills, the ridges almost certainly represent thrusting of active ice over the stagnant ice. Such a zone of thrusting would satisfy the requirement for compression between the southward movement of active ice and the stationary zone of stagnation. Panels of stagnant ice, separated by zones of shearing have been postulated in New England (Koteff and Pesl, 1981; Mulholland, 1982), where each sequence has outwash and/or proglacial lake. No evidence for either of these is observed in the Willseyville Trough, probably because of a very short time before the boundary between active and stagnant ice retreated to junction area of the Sixmile-Willseyville Trough and upper Sixmile valley. Oscillation of active ice front observed in that area indicates that the boundary remained here for some time, probably because ice there became constrained to a single tongue where melting would be slower. If so, sub-glacially transported debris would be deposited in the junction area and explain the paucity of exotic clasts in the zones of stagnation to the south.

The kettle-kame terrain has been identified as the Valley Heads kame moraine in the Willseyville Trough (e.g. Muller and Cadwell, 1986) but this identification needs some clarification. A similar terrain in the Inlet valley of the Cayuga Trough lies north of and behind a morphologically well-defined Valley Heads end moraine, which in turn lies behind an outwash plain (Olsen, 1962). In that case the kettle-kame terrain clearly formed as the ice stagnated behind the end moraine and is thus younger. The kettle-kame terrain in the Willseyville Trough may have initiated contemporaneously with the youngest section of the outwash plain but most of its development occurred well after deposition on the outwash plain ceased.

Data from western New York (Muller and Calkin, 1993) indicate that ice retreat from the Valley Heads position was underway by about 14.4 k 14C yrs bp. The 11.7 ka old organic lacustrine sediments of the kettle immediately behind the outwash head in the Willseyville Trough is consistent with this time of withdrawal, considering the time for the melting of the large block of ice responsible for the kettle and deposition of the underlying non-organic lacustrine sediments.
When the elevation of the ice surface at the north end of the Willseyville Trough fell sufficiently, water and sediment flowed from the upper Sixmile watershed through the ice margin channels at the base of Bald Hill onto the eastern kame terrace and/or onto the ice of the Willseyville Trough (Fig. 17). With the further drop in the ice surface both water and sediment from upper Sixmile drainage flowed through the fluvial channel at an elevation about 1020’ and onto the delta. The delta demands a lake but it seems to have been a local water body that formed at the junction between the ice tongues in the Willseyville Trough and upper Sixmile valley. It was not an early phase of the Lake Brookton that von Engeln (1961) envisaged as expanding into Lake Ithaca because a younger glacial advance covered the delta after the lake drained. Nevertheless, it might still best be termed “Lake Brookton”.

The easternmost exposures of the delta indicate that the elevation of this lake was initially at least 1000’. The forests remaining along the west wall of the quarry show that the lake level remained above 970’ but the foresets are overlain by till, indicating that some foresets and the topsets were removed by glacial erosion. The final lake elevation was most probably somewhere between 970’ and 1000’. It is quite likely that the lake level was tied to the hydraulic surface within a mix of ice and permeable sediment in the kettle-kame terrain to the south and onto the outwash plain.

The delta evolution was probably accompanied by the northward migration of feeder channels and conical foreset units and was possibly accompanied by minor degradation of the Willseyville outlet channel. At least one till occurs within the deltaic strata, which demonstrates that ice advances shrank or even destroyed this lake at times. The distribution of lacustrine strata indicates that, even at its largest extent, this lake did not extend far south of the delta but may have reached northward across the Sixmile valley.

A rough calculation of the delta volume, assuming the area shown on Plate 3 and a mean thickness of 50’ is 8.5x10^6 yds^3. Deposits in the delta consist almost totally of material transported as bedload from the upper Sixmile Creek watershed, which had been recently deglaciated. This bedload was undoubtedly a much higher fraction of the total flow than that of the present Sixmile Creek and the total flow was also probably higher. Present annual bedload is roughly 8x10^3 yds^3/yr at the Ithaca reservoir (Karig, et al., 2007), but at rates of even several times that, the delta would have taken at least a few hundred years to build.

The Willseyville channel, with a throat elevation of no higher than 965’, must have reached its fully developed form late in the history of the stagnation period because it transects the kettle-kame terrain. Most likely this channel development was associated with the drainage of Lake Brookton from an elevation of at least 1000’ to about 960’.

In planform this channel shows meanders with a wavelength of about 10,000’ and an estimated bankful width of about 700’. Empirical relations between meander wavelength and channel width (e.g. Leopold, 1994) are consistent, suggesting a formative flow on the order of 10,000 cfs. Such a rate of outflow could have cut the channel and lowered the overflow level to 965’ from that of the outwash plain extremely quickly. This suggests one or more glacial lake outburst floods, probably initiated by failure of an ice dam south of the lake.

The tills and ice contact sediments north of Sixmile Creek seem correlative with those just north of the delta and indicate local oscillations of an ice front around the junction area between the glacial trough and the upper Sixmile valley. The gravel clast composition indicated that the lower part of this sequence was predominantly glacier-sourced but that local sources, probably the upper Sixmile drainage contributed to the upper part. Drainage is assumed to have been southward through the Willseyville channel.

Exposures of the surficial till on the delta and north of Sixmile Creek clearly demonstrate that ice made one last advance over that area after Lake Brookton drained. The maximum position
Figure 23. Late Wisconsin moraines in the study area. Solid lines represent moraines documented in this study by field mapping and from Lidar imagery. Dashed segments are interpolated. Black = Valley Heads moraine. Yellow = Brooktondale moraine. The red and blue moraines are younger and unnamed. Note that the Valley Heads moraine occurs primarily in valleys whereas the younger moraines are confined to the interfluves. The black lines show the orientation and location of megaflutes from Lidar hillshade images and the red arrows show striae (ice motion directions) as mapped by Tarr (Williams et al., 1909). See Figure 1 for identification of features.
of that ice advance is marked by the morainal system that can be traced using the Lidar data and the field mapping of Tarr (Williams et al., 1909) from Inlet valley to the interfluve north of Sixmile valley and, with less certainty, to the Fall Creek valley (Plate 1, Fig. 23). The age of this advance can definitely be constrained only as younger than the Valley Heads retreat (14.4 ka $^{14}$C BP) and older than the Mapleton moraine, along Great Gully north of Aurora, dated at 12.65 ka $^{14}$C BP (Kozlowski, et al., 2014). Better constrained deglaciation records elsewhere suggest that this readvance correlates with the Hatfield event in the Connecticut Valley (Ridge et al., 2012) and the Little Falls advance in the Mohawk Valley (Ridge, 1992), which occurred about 13.5 ka $^{14}$C BP. This re-advance is tentatively given the same age and is here termed the Brooktondale advance.

It is unclear when meltwater from the ice front and drainage from the upper Sixmile watershed ceased flowing southward through the Willsseyville channel and began flowing northwesterly down the lower Sixmile valley. Flow apparently continued southward during deposition of the ice-contact sediments north of the delta and prior to the final ice advance but the channel across the delta indicates that it switched to sub-glacial northwesterly flow sometime during or just after that advance. The channel along Van Demark Rd overlays and is thus younger than the ice-contact sediments in that area. This channel is also at a higher elevation than the meander scrolls on the 960’ surface north of the delta. Together these constraints almost certainly tie this channel to the final glacial advance and also support northwest drainage into the ice. Neither this channel nor the cross-delta channel could have turned sharply under the ice to flow southward because their minimum preserved elevations are below that of the drainage divide of the gravel base in the Willsseyville channel.

The meander scrolls, at about the same elevation as the cross-delta channel, suggests subaerial flow, which would indicate that ice disappeared from the junction area rapidly.

Radiocarbon ages indicate that the pond in the Willsseyville channel south of the delta existed after ice retreat with drainage to the south and blockage to the north by deposits from the final glacial advance. This situation continued until Beaver Brook eroded headward and captured the drainage as far as the divide near Belle School Rd.

**UPPER SIXMILE WATERSHED**

Although the Sixmile-Willseyville Trough was the locus of major ice flow after the maximum advance of the Nissouri Stade, Late Wisconsin ice also moved from the Trough into the upper Sixmile valley and, at times, into that area from the Fall Creek valley to the north (Williams, et al., 1909). Yet another ice tongue moved southward in a through valley from the upper Casacadilla valley into the east-west section of the Sixmile valley west of Slaterville. These various ice movements left a complex array of glacial landforms in the upper Sixmile watershed.

From a glaciologic perspective the upper Sixmile watershed can be divided into two parts; the east-west trending section from Brooktondale to Slaterville and beyond, to another through valley and Valley Heads moraine, and the northerly trending headwaters section. This headwaters section can be further subdivided into the east and the west branches of Sixmile Creek. Each of these subsections of the upper Sixmile watershed has its own suite of landforms and is discussed separately.

**EAST-WEST SECTION**

**LANDFORMS**

The west end of the east-west section of the upper Sixmile valley logically begins where Sixmile Creek leaves the Sixmile-Willseyville glacial Trough, but that junction area has already been described because features there are closely related to those in the Trough. The east-west
section of the upper Sixmile watershed is a broad shallow valley that narrows eastward past Slaterville, where both flanks exhibit truncated spurs, and continues as a through valley into the Owego Creek drainage. Another through valley connects the Cascadilla Creek drainage with the east-west section of upper Sixmile valley west of Slaterville (Plate 5).

**Bedrock Valley**

The bedrock floor of the valley from Brooktondale to Slaterville lies about 200’ above that of the Sixmile-Willseyville Trough. The valley appears to have a shallow V-shaped cross-section based on refraction profiles and the few wells that reach bedrock (Miller, 2009). The thalweg of this bedrock valley is well north of the present Sixmile Creek on Miller’s refraction profile and based on minimum bedrock elevations (Plate 4), must pass close to well TM 994 at Caroline School, and lies near well TM 2028 in Slaterville (Plate 5). The Quaternary fill reaches at least 165’ in thickness in the thalweg but thins rapidly toward the valley hillsides.

**Through Valley**

East of Slaterville the east-west section of upper Sixmile Creek becomes another through valley leading to the Owego Creek drainage, with another Valley Heads moraine near the present drainage divide. As with the case in the Willseyville trough, but less pronounced, the Valley Heads moraine here is marked by an outwash head with an outwash plain that extends eastward into the West Owego Creek valley. Only a subtle possible overflow channel can be identified on this outwash, with a throat elevation near 1270’ (Miller, 2009). To the west of the outwash head is a limited area of kettles and kames (Plate 5).

A series of south-draining ice marginal channels and associated lateral moraines cuts the hill slope north of the Valley Heads ice margin (Plate 5). These features continue northwestward into the north trending section of Sixmile Creek valley (Plate 6). Other marginal channels to the north are probably part of same system but will be described in a following section. At its north end the highest channel has an elevation of 1560’, dropping southward to 1545’, where it turns easterly. Lidar topography shows that this channel crosses the ridgeline and drops into the headwaters of Owego Creek (Plate 5). This channel system has a broad flat floor and is bounded on the southwest by a lateral moraine. No bedrock is exposed along either side of this channel.

The most prominent channel, which starts in the north at an elevation of 1440, is that described by Rich (1908) and by Tarr (Williams, et al., 1909). This channel begins as a shallow trough but drops down a “waterfall” and continues as a narrow bedrock-bounded slot for about 1300 ft at which point one branch continues as a bench and the other drops sharply down slope (Plate 5), probably as a subglacial chute. A large lateral moraine bounds the channel along its entire western side until it drops onto the outwash plain, well beyond the outwash head. A third prominent channel begins at an elevation of 1325’ dropping southward to 1190’ over about 2300’, where it also debouches onto the outwash plain. There is an even lower channel that would have bordered the ice when the outwash head was being developed.

Short segments of other channels at the lower elevations indicate a complex history of channel evolution as the ice level fell. The highest channels must have developed when the ice front was beyond the outwash head because they enter the valley floor well east of that location. All the channels that flowed into the outwash plain drained eastward into the Owego Creek watershed.

**Kames and Moraines**

South and west of these channels and the outwash head is an area of very well developed kettles. A kettle-kame terrain also continues as a narrow, ill-defined band along the north side of the valley to 76° 23’ 50”W and north, up the tributary to Sixmile Creek at that point (Plate 5). These kettles and kames can best be associated
with retreat of Port Bruce ice because they lie just behind the Valley Heads ice front. Just west of this band and the tributary noted above is a Lidar-defined series of linear ridges that rise obliquely northwestward across the Sixmile valley and turn northward into the Cascadilla through valley (Plates 5 and 6). These ridges lie above the kettle kame band and within the area of upland till and are probably moraines formed when Port Bruce ice was still continuous between the Cascadilla and Sixmile valleys. The Lidar data indicates another probable moraine on south slope of Sixmile valley crossing Burns Rd and Central Chapel Rd (Plate 5). It is quite possible that this moraine correlates with that on the northern slope described above.

Cascadilla Through Valley

The through valley section of the Cascadilla valley, now draining southward into the Sixmile valley, has a well-defined channel, similar in character to the Willseyville channel. This was most likely a meltwater channel from an ice front or pro-glacial lake further northwest. The channel is bordered on both sides by terraces of uncertain affinity. These were interpreted as outwash by Tarr (Williams et al., 1909) and by Muller and Cadwell, 1986) and as both till and outwash by Miller (2009). The logs of the few water wells that might be applicable indicate a thin section of till over gravel. The Lidar data would support a till cover.

Alluvial Terraces

Along both sides of the E-W section of the Sixmile valley and below the kame terrane are alluvial terraces resulting from a west-flowing stream. However, the direction of flow when this stream reached the Sixmile-Wilseyville Trough changed as this terrace sequence evolved. The highest terrace on the south side of the valley at its western end is at an elevation above 1000’ and is associated with the higher of the two channels that appear to have fed the delta. The responsible stream would thus have flowed south into the Wilseyville Trough prior to the Brooktondale ice advance.

The highest terrace north of the valley at the same longitude is at a significantly lower elevation (~900’) and clearly marks drainage into the Sixmile Trough. This terrace is far below the surficial till from the Brooktondale advance and is thus younger than that event. It is also lower and younger than the alluvial terraces on the 960’ surface north of the delta.

LITHOLOGIES

The sedimentary sequence in the E-W section of upper Sixmile valley is known almost entirely from well logs except for exposures along Sixmile Creek. The dearth of information concerning lithologies in this area allows only general conclusions to be made.

At the eastern end of the E-W section, where Sixmile Creek begins its N-S trend, there are two tills, separated by a thick section of fluvial/lacustrine sediments that are described in the next watershed section. The uppermost till lies on the present valley northern slope and can be associated with the Valley Heads advance. This till probably continues on the surface westward, north of the band of kames.

The lower till is exposed in the creek bottom and is most logically attributed to the Nissouri Stade. Till is exposed discontinuously down the Sixmile channel, and is overlain by a thin cover of fluvial deposits, but where the creek turns southward downstream, south of the Caroline school, the till in the creek appears to correlate with the till north of and beneath the band of kames. Perhaps the Valley Heads (Port Bruce) and Nissouri tills have merged on the northern slope of the valley. Beneath the till in the stream channel is a sediment section over 100’ thick that includes undefined sand, gravel and clay, possibly including more till (e.g. TM 994; Miller, 2009). This section is most probably pre-Nissouri in age.
INTEGRATION OF LANDFORMS AND LITHOLOGIES

The seismic section across the east-west section of the upper Sixmile valley indicates a V-shaped fluvial chapter to its pre-Nissouri history (Plate 4, section I-I’), but little else can be said about that period. Nissouri ice clearly covered the entire area, as shown by the till-covered hilltops. An advanced Valley Heads phase of the Port Bruce Stade is demonstrated by the ice margin channels that extend well beyond the Valley Heads outwash head as well as by several kettles in the outwash plain.

This Valley Heads outwash plain was thought to have dammed a minor and early pro-glacial lake (Williams, et al., 1909; von Engeln, 1961) upon ice retreat, but no lacustrine sediments were observed during this study that could be attributed to such a lake. If such a lake existed, it must have been for only a very short period of time. Rather than a lake, a complex of ice masses and standing water that initially drained into Owego Creek is more likely to have developed, but this phase also would have been very short-lived because the sediment load from the N-S section of Sixmile Creek did not have time to construct a recognizable delta into the area west of the outwash head.

Drainage into Owego Creek continued only until the hydraulic surface dropped below the 1270’ outlet, caused either by the drop of the ice surface at the junction with the Willsieville Trough to this level or by the development of a sub-marginal channel that would carry water from the upper Sixmile valley into the Willsieville Trough. Such a channel may be represented by the highest of the ice margin channels at the base of Bald Hill (Plate 3). The preserved segment of this channel has a maximum elevation of 1230’ but would have headed at a greater elevation in the upper Sixmile valley.

The withdrawal of ice from the Valley Heads position was more likely to have been by stagnation and downwasting than by ice front retreat, leading to a kettle-kame terrain similar to that in the Willsieville Trough. A minor re-advance during this period could have been responsible for the moraines observed on both sides this valley section. The subsequent disappearance of the ice connection between the Cascadilla and upper Sixmile valleys led to a poorly defined sequence of drainage elements from the ice in the Cascadilla valley into Sixmile Creek. The development of stream terraces in upper Sixmile Creek across the Cascadilla channel indicates that this drainage ceased relatively early in the degradation history of Sixmile Creek.

NORTH-SOUTH SECTION

LANDFORMS

Bedrock Valley

The oldest recognized Quaternary landform in the north-south section of Sixmile Creek is a buried bedrock valley that underlies this section of the present valley, at least from the area of the junction between the east and west branches of Sixmile Creek downstream to the east-west Sixmile valley section. This bedrock valley was recognized by Hausman (1918), based on the westward sloping bedrock surface just west of the creek junction and a well near the junction of Midline, Irish Settlement, and Hurd roads (a locality then called Van Pelt’s) that reached bedrock only 20’ below the surface and at an elevation of 1350’. A profile of passive seismic stations down west Sixmile Creek between these two locations revealed a V-shaped bedrock valley with at least 150’ of relief (Plate 4, Section J-J’). The bedrock valley is filled with a variety of deposits, described later, that have been dissected by the post-glacial Sixmile Creek.

The trend and location of this buried bedrock valley away from the junction area remains to be determined but the bedrock surface along Sixmile Creek valley downstream to 42°24’15” shows a clear westward slope, which appears to mark the...
east side of this valley. Moreover, bedrock exposures in the creek bed terminate downstream at the gas pipeline crossing as a steep NW trending scarp, suggesting that this buried valley crosses the present valley here and heads downstream in a more easterly direction. It is likely that this buried valley drained eastward into the Owego Creek valley, but this conclusion requires more subsurface data than are available.

Terraces and Valley Fills

Along the western side of this section of the Sixmile Creek valley is a dissected high-level terrace (Plate 6). Segments of this terrace can be traced southward along the west side of the valley to just south of the pipeline crossing (Plate 6) but sediments that underlie the terrace are also observed east of Sixmile Creek further south, suggesting that the drainage system responsible for the terrace and related sediments also flowed into the present Owego Creek watershed.

This terrace surface continues north of the creek junction, up east Sixmile Creek, where it becomes less dissected and appears to form the valley floor. The 2’ contours of the recent Lidar topography illuminates the broad flat floor of this valley all the way to the divide with the Fall Creek watershed and includes the floors of the valleys tributary to east Sixmile Creek. This flatness reflects aggradation of these valleys, which cannot be entirely explained by sources within the Sixmile watershed because the fill extends to the watershed divide. As concluded by Tarr (Williams et al., 1909), a major source must have been to the north, from the ice in the Fall Creek drainage. The valley of west Sixmile Creek also has a flat floor, which is broader west of Midline Rd than downstream where this surface lies well below the floor of the upper section of east Sixmile Creek and the high terrace at the junction (Plate 6), and is thus younger.

A post-glacial alluvial terrace, now about 20’ above the present stream, forms the valley floor from not far below the stream junction downstream to the highest terrace along the northern side of the E-W valley section (Plate 5).

The N-S section of Sixmile Creek becomes entrenched in a bedrock gorge several thousand feet downstream of the stream junction and remains entrenched for a short distance up the west branch and much further up the east branch (Plate 6)

Moraines

Hausman (1918) identified a number of moraines in the upper Sixmile drainage, some of which are questionable, but his Moss Creek moraine, which crosses Midline road a few hundred yards south of Van Pelts (Plate 6), is well documented. This moraine is a NW trending ridge, convex toward the northeast, composed of till and overlying the high-level terrace at its eastern end. There may well be a minor moraine (Hausman’s Spur Creek moraine) just north of the Moss Creek moraine and west Sixmile Creek, which probably was diverted between the two moraines subsequent to their formation (Hausman, 1918). Both these moraines separate an irregular kame-dominated terrain to the south from the high-level terrace surface and broad flat valley floor of east Sixmile Creek to the north and are here correlated with the Valley Heads moraines on the valley floors.

Ice Margin Channels/Moraines

A series of ice margin features occurs along the east side of the N-S section of Sixmile Creek south of the creek junction, the southernmost of which were described in an earlier section. Those further north are discontinuous, appearing only on the ridges (Plate 6), as noted by Tarr (Williams, et. al., 1909) and Rich (1908). These features are benches or ridge-swale pairs that could be moraines or ice margin channels or both, but certainly mark ice edge positions. The higher channels/moraines lie at ~1600’ and would seem too high to correlate with the Moss Creek and Spur Creek moraines on the west side of the valley, which are only slightly above 1400’. These higher channels are poorly preserved, and, as concluded by Rich (1908), are probably older than the Valley Heads moraines. They possibly represent recessional features formed following the Nissouri stade advance.
Features Associated with West Sixmile Creek

The source of much of the sediment in west Sixmile valley appears to be in the vicinity of the Cornell University Ringwood Wildflower Preserve, just beyond the Sixmile watershed divide.

This is an area of prominent kettles and kames, transected by a north-south trending esker (Plate 6), which extends northward to and beyond the kettles to what appears to be a fan on the Lidar hillshade image. The esker is sharply truncated at its south end against a NW trending ridge, which may be a moraine, south of which the elevation drops sharply (Plate 6). This esker and the kettle-kame complex, which are unusual for their location in an upland area, were recognized by Tarr (Williams et al., 1909, p. 171), who felt they “formed during the melting of an ice tongue… from the north”. The steep drop in topography south of the esker and kettle-kame terrain leads to an alternative interpretation that that area was occupied by a relatively thin tongue of ice protruding northward from the main Port Bruce ice mass. This would better explain the fan at the north end of the esker and the supply of sediment to the west Sixmile valley. Sections of what is identified from Lidar data as the Valley Heads moraine on the north flank of Mt. Pleasant (Fig. 23) lie at an elevation of about 1700’. The moraine is interpreted as wrapping around the Mt. Pleasant ridge line, which would support eastward ice flow into the Ringwood area.

LITHOLOGIES

Most of the lithologic data from upper Sixmile Creek are from the deposits that fill the buried bedrock valley. These consist of a pair of tills separated by a lacustrine/fluvial sequence. Well TM 1300, drilled near the buried valley thalweg, penetrated about 150’ of these deposits and bottomed in a gravel aquifer, which may represent even older fluvial sediments (Section J-J’, Plate 4).

In the creek bottom near the stream junction the basal till lies on bedrock, which there forms the eastern side of the buried valley. Downstream from where bedrock exposed, till occurs intermittently in the stream bottom at least as far as Slaterville. This till is a clay matrix dominated diamicton, very similar to the late Wisconsin lodgement tills found elsewhere in the Sixmile system.

Because this till is below the surficial till that is assumed to be Port Bruce (Valley Heads) in age, it is here interpreted as of Nissouri age. The till at elevations above the extent of the Valley Heads advance is also interpreted as of Nissouri age, but in the uplands it is a clay matrix diamicton, the clasts of which are almost totally angular and of local origin.

The lacustrine/fluvial interstadial sequence is exposed along the west side of the N-S section of Sixmile Creek from upstream of the creek junction to the high bank near the Moesch well, where it lies on the lower till (Fig 24), and also east of the creek in this downstream area (Plate 6). This distribution of exposures strongly suggests that the sequence is confined to the fluvial bedrock valley.

This interstadial sequence coarsens irregularly upward, from a basal silt or fine sand to coarse

Figure 24. Basal Erie interstadial lacustrine silt and fine sand in the N-S section of upper Sixmile Creek. The contact between the well-bedded silt and the Nissouri lodgement till is just above the shovel blade.
gravel or cobble at its top. Both current-bedded sand near the base and imbrication of gravels indicate a southward water flow. Ninety percent of the gravel clasts in this sequence are from local sources, except for a sample from the area east of the creek, which had almost 20% exotic clasts (Appendix 2; bags 24, 34, 36, 37, 39).

This sequence is interpreted as having been sourced from the uplands in the headwaters of east Sixmile Creek as well as from an ice front that overtopped the divide from the Fall Creek valley. Deposition was initially into an ephemeral lake, trapped north of the ice front in the E-W section of upper Sixmile Creek. Filling of this lake led to a fluvial system, which drained into Owego Creek.

Capping the lacustrine/fluvial sequence is a surficial till that can be traced into the Valley Heads Moss Creek moraine and is thus identified as (Valley Heads) Port Bruce in age. On the higher terrace this till is 10-30’ thick and contains a high percentage of large clasts, of both local and exotic origin. A road cut through the Moss Creek moraine reveals a very heterogeneous mixture of local and exotic larger clasts, many of which are quite round, and are set in a matrix that varies from clay to sand. Smaller clasts are dominantly of local origin, platy and angular (Appendix 2, bag 94).

In the Ringwood Preserve area the lithology of the esker was examined in a large pit dug in the north-facing scarp of the gap in the esker’s central section, and near the esker crest (Plate 6). The esker lithology consists of well-graded clasts from silt to cobbles approaching boulder size. The unusual aspect of this material is that it consists almost totally of local shale and siltstone clasts (Appendix 2; bags 86, 87) that range from round to extremely angular. This implies a local source of material, already water worn but broken by glacial action. A problem with a local source is the clear clast imbrication indicating flow from the north, which should have supplied more exotic material.

The till exposed in the Ringwood Preserve is presumed to be of Valley Heads age because it is intimately associated with the kettle-lame terrain and esker of that age. Clasts in this till are dominantly (>90%) of local origin (Appendix 2) and mostly angular, but with a few ranging to sub-round.

INTEGRATION OF LANDFORMS AND LITHOLOGIES

The oldest discernible Quaternary feature in the N-S section of Sixmile Creek is the bedrock fluvial valley. This valley is older than the basal till, which is assumed to be of Nissouri age. The N-S valley of Sixmile Creek was probably not a major flow path for ice, so the Nissouri ice didn’t significantly erode the valley, which retained its fluvial cross-section.

Lacustrine/fluvial sediments in this valley were deposited during the retreat of Nissouri ice, in part when ice still filled the Fall Creek valley and extended over the divide at the top of east Sixmile valley. Sediments from this ice mass and from tributaries to east Sixmile Creek were deposited in the N-S section of the creek in front of ice occupying the E-W section of Sixmile Creek. Drainage continued from this depocenter into Owego Creek, as documented by the fluvial sediments east of the creek, but the details of this blockage are unknown because relevant data largely have been removed or covered during the subsequent Port Bruce advance.

The ice advance during the Port Bruce Stade reached the creek junction as marked by the Spur and Moss Creek Valley Heads moraines and by the till sheet to the south. It is possible that the Spur Creek moraine represents the advanced Valley Heads phase. The extent of the Valley Heads advance is interpreted as following the lower ice margin channels southward to the outwash head east of Slaterville and extending northwestward into the Ringwood Preserve area (Plate 6). This would define an ice mass in upper Sixmile drainage moving primarily to the east rather than to the north (Hausman, 1918).

The occurrence of the kettle-kame terrain and esker in the Ringwood Preserve, high up on the valley side suggests that stagnation and drainage
of thin ice in that area was due to a hydrologic system that was isolated from that of the main ice mass, somewhat like a perched aquifer. The esker possibly served to drain some of this kettle-kame area as that ice melted, but the drainage history remains conjectural.

Hausman (1918) presented a plausible model in which drainage from west Sixmile Creek prior to the Valley Heads advance was southward down a Sixmile tributary, which he called Gravel Creek, lying west of and parallel to the N-S section of the present Sixmile Creek (Plate 6). That path was blocked by the development of the Moss Creek moraine and flow was diverted into Sixmile Creek along the northeast flank of the moraine. Such a scenario is supported by well data (TM 2135, Plate 6) indicating a bedrock low beneath the moraine where the pre-glacial stream would have flowed. It would also explain the sudden widening of the alluvial fill in west Sixmile Creek above Midline Rd because the creek was forced to aggrade to the divide between Gravel Creek and Sixmile Creek when it was diverted.

As explained by Tarr (Williams et al, 1909) and Hausman (1918), the development of the Moss Creek and Spur Creek moraines also forced the drainage of Sixmile Creek to the east side of upper Sixmile Creek Valley, resulting in the formation of the lower ice margin channels and, finally, the bedrock gorge in that vicinity.

Drainage from the Ringwood Preserve kettle-kame terrain was probably initially down the new west Sixmile Creek, but the imbrication of the clasts in the upper, younger section of the southern half of the esker points to a southward flow, into the major ice mass, during the final stages of esker activity. A possible reason for such a change in flow direction is that the hydrologic barrier between the Ringwood area and the main mass disappeared allowing flow into the main mass and exiting at the ice front in the Sixmile valley.

**EVOLUTION of the SIXMILE WATERSHED**

The previous sections of this report presented descriptions and glacial histories of the sub-units into which the Sixmile Creek watershed was divided. Only partial histories could be determined for each sub-unit, with early events best expressed in the Sixmile Trough and more recent events best controlled by features in the Willsseyville Trough and the upper Sixmile drainage. These histories are here combined to produce a consistent and plausible glacial evolution of this watershed. How this interpretation fits the glacial evolutionary model for the larger Cayuga Trough system and for the Finger Lakes region is also discussed. Although the glacial history of any area within this region must be compatible with the larger history, it must also be recognized that any regional history is the construct of individual local histories.

**PRE-WISCONSIN HISTORY**

A firmly dated glacial history in the Sixmile watershed begins with the ice advance of the Mid Wisconsin Sub-stage into the Sixmile Trough. However, there is reasonable evidence for a Sangamon age of the 600’ interglacial gorge and an Illinoian age for the till that was interpreted as associated with the erosion of the inner glacial trough. Earlier gliation in this area is documented by the outer glacial trough, but there are no chronological constraints associated with this feature.

The Illinoian stage appears to be an interval associated with major glacial erosion in the Cayuga Trough region. Not only is the presumed Illinoian inner glacial trough in the Sixmile Trough deeply entrenched into the outer glacial trough but the 600’ gorge was incised over 100’ into the inner glacial trough, which was a hanging valley with respect to the Cayuga Trough (Tarr, 1904b). This requires that deep glacial entrenchment also occurred in the Cayuga Trough during the Illinoian stage.
The base level for the 600’ gorge, extrapolated to the center of the Cayuga Trough, is about 25’ above the surface of Lake Cayuga (Rich & Filmer, 1915) and is compatible with the Sangamon Fernbank lacustrine deposits that lie up to about 40’ above the western shore of the present lake (Karrow et al., 2009). Moreover, the Fernbank deposits represent some water depth and the shoreline would have been at a higher elevation. Other features that might be of Sangamon age are the upper reaches of the hourglass tributaries, which appear to be part of the 600’ gorge fluvial system.

MID-WISCONSIN SUB-STAGE

Mid Wisconsin deposits of two distinct ages were mapped in the area near the 60’ dam. The older, 42 ka plant bearing strata, were found at only one site but reworked plant material of that age was found in younger Mid and Late Wisconsin strata at several sites, implying a larger source and/or a cold period during which organic material was preserved.

The bulk of the Mid Wisconsin deposits, which overlie presumed Illinoian till, have been attributed to an ice advance during the Cherrytree Stade of the Mid-Wisconsin Sub-stage (Karig and Miller, 2013). Although there is little doubt that a pro-glacial lake was overrun by ice in the Sixmile Trough during this stade, the interpretation that the resulting till formed a terminal moraine for that advance is more speculative. This interpretation is consistent with evidence for a Cherrytree ice advance of similar age along the Genesee River valley (Young and Burr, 2006), about 75 miles northwest of Ithaca.

The 200’ gorge was most likely cut during the Plum Point Interstade. The base level for this stream was more than 60’ lower than that for the 600’ gorge system and even lower than that for the present Sixmile Creek. A Plum Point base level lower than that at present might be due to less crustal rebound during that short interstade than during the Holocene. The fact that the 200’ gorge is shorter than the post-glacial gorge supports this supposition. The only other feature of pre-Late Wisconsin age recognized in the study area is the bedrock valley in upper Sixmile Creek, which is pre-Nissouri in age, but no other age constraints were obtained. It could well also be of Plum Point age.

LATE WISCONSIN SUB-STAGE

NISSOURI STADE

The Late Wisconsin, marking the maximum advance of Wisconsin ice, was first heralded in the Cayuga Trough region by a pro-glacial lake south of the advancing ice front. Sediments deposited in this lake are preserved as deformed masses exposed within the lower half of the till in the Sixmile Trough and almost certainly constitute the major protolith for that clay-rich till. The argument was made earlier that the single till observed in most of the Sixmile Trough represents a continuous ice cover in that area from some time before the Nissouri maximum until ice withdrawal following the Port Bruce Stade.

Another question is how much of the lacustrine sediment that served as a protolith for this till was excavated from the Cayuga trough and how much from the Sixmile-Willseyville Trough. The great thickness of till in the Sixmile Trough, even at its mouth, would suggest that much or most of the lacustrine sediment was derived from the Cayuga Trough but the protolith deposited within the Sixmile Trough must have been deformed and transported within that trough.

The duration and surface elevation of the proglacial lake south of the Nissouri ice front is unknown but when it occupied the Sixmile-Willseyville Trough it must have drained southward from the Willseyville Trough and at least at the 700’ elevation of the bedrock sill in the through valley. Because of the thick section of sediment there, the lake elevation was almost surely much higher.
In addition to removing pro-glacial lacustrine deposits in the Cayuga Trough, the Nissouri ice probably was responsible for the removal of much of the pre-Late Wisconsin strata in the Sixmile Trough. Downstream of the 30’ dam, till lies directly on bedrock, even on the floor of the 600’ gorge. Progressively further to the southeast pre-till sediments occur, first within the 600’ gorge and by German Crossroad, as a thin band across much of the floor of the inner glacial gorge. The stratigraphy of the nearly 300’ of the Quaternary section in the Willseyville Trough is unknown, but the Valley Heads till lies close to the surface, (e.g. Plate 4, Section H-H’) leaving more than enough room for a significant thickness of pre-Nissouri strata. The inverse of a SW increase in a pre-Nissouri section leads to the conclusion that the great bulk of pre-Late Wisconsin deposits were removed from the Cayuga Lake section of the Cayuga Trough by Nissouri ice.

Although the Nissouri ice advance was the most extensive of the Wisconsin Stage and covered the study area to depths of up to over 5000’ (e.g. Bloom, 1986), it appears to have been a period of relatively little bedrock erosion, at least in the Cayuga system. Tarr (Williams et al., 1909) reached this conclusion primarily because of the preservation of weathered bedrock surfaces but it is also supported by the existence of pre-Nissouri deposits at the base of much of the Sixmile Trough. Moreover, the thick Late Wisconsin till in the trough suggests deposition rather than erosion during that time.

On the other hand, the very large angular blocks of Tully limestone and Ithaca formation siltstone and sandstones observed near the base of the till in the Sixmile Trough require some local glacial erosion. Because these strata would have lain above the base of the Cayuga Trough from Ithaca northward by Nissouri time, most of this erosion must have been from the flanks of the two troughs. Tills within the glacial troughs have a high percentage of exotic clasts of all sizes, attributed by Moss and Ritter (1962) to reworking of older glaciofluvial deposits in those troughs. On the uplands the thin cover of till with angular clasts, almost entirely local in origin, also requires some erosion but neither the Nissouri ice nor earlier ice advances accomplished enough erosion to erase the pre-glacial fluvial topography of the upper valley slopes.

The paucity of glacial erosion of the uplands has been recognized (e.g. Muller, 1963) but the reason for this paucity has not been made clear. Glacial striae of Nissouri age trend west to southwest over the uplands south of the Valley Heads moraines (Fig. 23) and probably over all uplands of the study area. This defines a general flow direction at high angle to the troughs but the restriction of exotic-rich deposits to the troughs indicates that ice streams existed along the troughs, with higher flow velocities, which probably transported the bulk of the advancing ice.

Ice flow over the the uplands was in the direction of the ice surface gradient but was much slower. Slower ice velocities in the higher areas away from the troughs would not only lead to less erosion by itself but would also favor a colder base because less basal frictional energy would be generated. It is quite possible that the ice sheet in the Cayuga area was polythermal, especially during the colder, advance periods, with cold-based conditions in the uplands.

**ERIE INTERSTADE**

Retreat of the Nissouri ice from its maximum extent began about 21k 14C yrs bp in western NY (Muller and Calkin, 1993) and probably about the same time in the Cayuga area. This retreat led to the Erie Interstade, but the nature and extent of ice retreat during this interstade is controversial. Some workers (Morner and Dreimanis, 1973; Ridge, 1997) have suggested that the ice front at this time retreated into the Erie and Ontario basins, with eastward drainage through the Mohawk Valley, although others are skeptical about some aspects of this scenario (Muller and Calkin, 1993; Dyke et al., 2002). The evidence from the Cayuga Trough region does not support
such a large-scale retreat of Erie Interstade ice.

Observations during this study support Muller’s (1957) conclusion of a single till in most of the Sixmile Trough and it was argued earlier that this single till spans Nissouri and Port Bruce stades. On the other hand, several Late Wisconsin tills were recognized in the southeastern end of the Sixmile Trough, the upper Sixmile drainage and in the Willseyville Trough. Well logs near the junction of these three units record the transition, where two tills, separated by lacustrine silt and fine sand, merge northwesterly into a single till (Fig. 22). This would appear to define a proglacial lake and to mark the maximum retreat of the Erie ice in the Sixmile-Willseyville Trough.

Corroborating evidence for an Erie interstade retreat only to the Ithaca area has recently been found in Inlet Valley (Karig and Ridge, 2015). In Inlet Valley a thick (>100’) section of clay underlies Port Bruce deposits. This section is penetrated by boreholes near the Valley Heads end moraine (Karig, 2004) and is exposed along Inlet Creek and several of its tributaries. Striated dropstones in this clay identify the sequence as proglacial. Boreholes in the Cayuga Inlet (Tarr, 1904a; Lawson, 1977) show no such sequence, but only a single till underlying a younger proglacial section, which indicates that the ice front blocking the Erie proglacial lake was south of Cayuga Lake.

The data supporting an Erie Interstade ice retreat into the Mohawk Valley is compelling (e.g. Ridge, 1997) but the case for eastward drainage from the Erie-Ontario lowland into the Mohawk Valley is more conjectural (Ridge, 1997). It may be that, because the Cayuga Trough lies in the area with the lowest elevations across the Appalachian Plateau, the ice was thickest there and resisted retreat. Clearly the subsequent ice readvance during the Port Bruce Stade went furthest south in that area (e.g. Ridge, 1997).

The only other feature in the study area that could be associated with the Erie Interstade is the sediment section that overlies Nissouri till in the filled bedrock valley in the N-S section of upper Sixmile Creek. Apparently these were deposited when ice had retreated down that valley but still occupied the Fall Creek valley, from which meltwater spilled into the Sixmile drainage. The coarsening upward sequence from a basal fine to medium grained sand suggests that initially there was a lake briefly caught between the two ice masses and that this lake drained into the Owego Creek watershed. With time the lake filled with prograding coarser sediment.

PORT BRUCE STADE

The ice advance that marks the subsequent Port Bruce Stade is more than a single pulse to and from the Valley Heads moraine in the Sixmile watershed. Muller (1964) has presented evidence for an “advanced Valley Heads” ice front preceding the relatively stable ice front position of the Valley Heads moraine in several parts of the Finger Lakes region. Perhaps the best local example is in the Inlet Valley of the Cayuga Trough, where large kettles (Spencer Lake and Spencer swamp) and ice margin features (Karig, 2004) demand a pre-Valley Heads ice advance that reached at least several km south of the Valley Heads end moraine. Evidence for advanced Valley Heads positions in the study area are the ice margin channels that would have emptied on the valley floor well in front of the Valley Heads outwash heads as well as several kettles in the outwash east of Slaterville.

One notable characteristic of the two Valley heads moraines in the study area is their very extensive outwash plains and paucity of visible end moraines, which, as surmised by Tarr (Williams, et al., 1909), may lie buried in outwash. Even during this period of relatively stable ice front position, tills interbedded with the outwash of the Willseyville Trough show fluctuations in that position of over 0.5 mile.

How sediment was supplied to the outwash plain in the Willseyville Trough is not obvious. It is clear that the local clast fraction increases upward and that the youngest sediments were transported, at least in part, along the kame terraces but there are a number of processes that
might explain these observations. The exotic-rich lower levels in the outwash indicate a glaciogenic input but this material could have been entrained in basal ice, been eroded from sub-glacial sediments or transported via sub-glacial flow from far to the north. Mullins, et al. (1996), Shaw and Gilbert (1990), and others have postulated significant to large sub-glacial flow along the Cayuga Trough during the Port Bruce Stade to explain the Valley Heads moraines and the drumlin fields to the north. The bedrock sill in the Willseyville Trough (~700') is significantly lower than that of the Cayuga Trough (~1000') (Miller and Pitman, 2012), and although the surface elevation at the time of outwash deposition would have been higher by the amount of older Quaternary sediment overlying bedrock, it is almost certain that a large fraction, if not all of such sub-glacial flow would have had to exit the ice margin in the Willseyville Trough.

No evidence of eskers, tunnel valleys or other channelized flow features to document such sub-glacial flow were observed in the kettle-kame terrain of the Willseyville Trough. Concentrated flow features might have existed while the ice was still active but were destroyed by subsequent ice motion. Alternatively, sub-glacial sheet flow might have been the dominant agent of transport. This question remains unresolved.

As Tarr (Williams et al., 1909) noted long ago, there is much less evidence of the Valley Heads moraines on the valley slopes than in the troughs. Lateral moraines, which constrain ice margin channels, are well developed northeast of the ice front ramp in the Willseyville trough but these can be traced behind the ice front only a half mile or less. A similar condition exists north of the outwash head east of Slaterville. As previously suggested, this lack of Valley Heads lateral moraines could reflect the absence or paucity of detritus on the ice surface behind the ice tongues in the troughs, as well as concentration of sub-glacial transport along the trough floors.

There are, however, several moraines in the upper Sixmile drainage that can reasonably be identified as Valley Heads in age and, together, provide a rough outline of the limits of the Valley Heads ice in the upper Sixmile drainage (Fig 23). The locations and elevations of these moraine segments require that the ice moved ESE in the upper Sixmile area rather than to the east or northeast as deduced by Hausman (1918). Megafilutes (Fig 23) and striae (Williams et al., 1909) in the region including the study area show that ice movement during the Pt. Bruce Stade followed the glacial troughs and axes of other low lying areas.

Clasts near the top of the Late Wisconsin till in the Sixmile-Willseyville Trough, and thus Valley Heads in age, are exotic-rich, also indicating ice flow dominantly along the glacial troughs. As with the Nissouri till, the Valley Heads till in the uplands of the study area are dominated by clasts of local provenance. This strong partitioning of clast distribution indicates that all or nearly all sediment was carried near the ice base. This conclusion differs somewhat from that of Moss and Ritter (1962), who felt that Valley Heads tills were generally exotic-rich, with high limestone concentrations. They also felt that Valley Heads tills had a coarser (sandier) matrix than did Nissouri tills. In the present, less detailed study the tills of the two ages were felt to be lithologically indistinguishable.

The features resulting from the ice front retreat from the Valley Heads advance position have not been significantly overprinted by subsequent advances in the Sixmile watershed and the wealth of data preserved demonstrates that this retreat was far from a simple continuous withdrawal of the ice cover.

Features in the kettle-kame terrains behind the Valley Heads outwash plains in both the Willseyville Trough and the upper Sixmile drainage indicate that ice withdrawal was more by stagnation and downwasting than by ice front recession. The differences between the behavior of the two ice tongues is, in part, because the ice was much thinner in the hanging upper Sixmile valley and because sediment laden meltwater drained into the Willseyville Trough from the upper Sixmile watershed, where it eroded kames and deposited thin terrace gravels. Details of the evolution of both ice tongues were given in
earlier sections but, in general, the active ice front tended to remain near the ice tongue junction, probably because melting was markedly reduced where the ice was concentrated in a single tongue. Lake Brookton was an ephemeral feature that formed at this junction but could not have evolved into proglacial Lake Ithaca because of the subsequent Brooktondale re-advance that covered the lake site at about 13.5 ka.

The Willseyville channel is most likely to have formed during one or more draining events (jokulhlaups?) of Lake Brookton. It must also have served as the channel for drainage from both the upper Sixmile watershed and the Willseyville Trough between the time of lake emptying and the glacial re-advance. The question as to whether this channel ever served as the outlet to Lake Ithaca is discussed in a following section.

The Brooktondale re-advance left a moraine that can be traced in the uplands fairly confidently from the east side of the Cayuga Trough to the interfluve between Sixmile and Cascadilla creeks and less reliably into the Fall Creek valley (Fig 23). It is puzzling that this and younger moraines in the region occur primarily on the uplands, whereas the Valley Heads moraines are confined almost entirely to the troughs.

During the almost 2000-year interval between the retreat from the Valley Heads front at 14.4 ka and the Mapleton moraine north of Aurora at 12.65 ka, the ice front had only retreated about 4.2 miles in the Willseyville Trough by the time of the Brooktondale re-advance at 13.5 ka, at an average rate of only 25'/yr. In contrast, during the second segment of this period the ice front retreated about 30 miles at an average rate of ~200'/yr.

The Brooktondale re-advance also just preceded a very large and rapid increase in average temperature as recorded in the Greenland ice cap (Rasmussen et al., 2014). Not only does the date of this warmup constrain the interpreted age of the Brooktondale re-advance but would also explain the subsequent rapid ice recession.

MACKINAW INTERSTADE AND YOUNGER

Two major observations made during this study that are related to the events that followed the Brooktondale re-advance lead to an interpretation at great odds with the orthodox model of a persistent proglacial lake south of the ice front in the Cayuga and Sixmile troughs. The first such observation was the lack of lacustrine and deltaic sediments above an elevation of 780-800' in the Sixmile Trough. This lack of proglacial lake deposits has been attributed to the short duration of Lake Ithaca and to post-glacial erosion but the available data indicate otherwise.

A Lake Ithaca beginning after the Brooktondale re-advance and lasting until its demise by drainage through the Ovid outlet (e.g. Fairchild, 1934), which isn’t far south of the Mapleton moraine (Kozlowski et al., 2014), would have persisted for around 700 years. Gross sedimentation rates in the Cayuga Trough can be estimated from seismic reflection profiles (Mullins, et al., 1996), which show that about 80m (250’) of sediment were deposited from the initiation of lacustrine conditions until the demise of Lake Iroquois at 11.7 ka. Mullins’ seismic sequence 3 might represent a sub-glacial (Mullins and Hinchey, 1989) or early pro-glacial (Mullins et al, 1996) condition but, in either case lead to average sedimentation rates of well over 0.5’/yr. In the Sixmile Trough initial sedimentation should have been of coarser grained clastics from the ice front as well as from the upper Sixmile drainage, leading to significantly higher sedimentation rates. It is hard to escape the conclusion that at least several 10’s of feet of lacustrine sediment should have been deposited in the southeastern section of the Sixmile Trough in a Lake Ithaca with a surface elevation near 960’. Although some of the upper, less consolidated lacustrine clays might have been removed by erosion, it is not at all likely that all the section was everywhere so removed, especially the coarser-grained and more consolidated lower section. In addition, had there been a Lake Ithaca with an outlet near 980’, a significant delta should have formed in the area.
north of the Brooktondale delta, for which there is no evidence.

The second critical observation was that drainage from the upper Sixmile watershed during or just after the Brooktondale re-advance was into the ice front. This would seem to be impossible and to violate the need for flow to be down a hydraulic gradient, but this need not be the case. Assuming that the Brooktondale re-advance correlates with the Little Falls advance in the Mohawk Valley (Ridge, 1992), or is even just in that rough time frame, the Laurentian ice front would have been somewhat upstream of Herkimer in the Mohawk Valley, the proposed outlet (Fig 25). At present that location is at an elevation of about 400’, from which at least several hundred feet of differential rebound (Pair and Rodrigues, 1993) must be subtracted for its elevation at the time of the proposed drainage. If there were hydraulic continuity from the ice front in the Sixmile Trough to the Mohawk Valley, there is a more than adequate hydraulic head. The most likely flow path for the postulated sub-glacial drainage between these two points would have been northward along the Cayuga Trough and eastward along the Syracuse channels or elsewhere in the Oneida Lake lowlands (Fig 25).

There was almost certainly some form of hydraulic continuity along this path because the Laurentian ice, at least south of the Ontario basin,

Figure 25. Present physiography of the eastern Finger Lakes and Oneida Lake region showing the extent of glaciation during the Brooktondale re-advance following the Valley Heads advance (approximately 13.5 ka yrs bp) in light blue. The ice margin around the Ithaca area is from this study and that in the Mohawk valley from Ridge (1992). The margin between is a rough interpolation. The red lines show the postulated sub-glacial flow from the Brooktondale delta into the Mohawk River just following this re-advance. It is assumed that there was much additional sub-glacial flow from other sources along the glacial margin and perhaps from the eastern Great Lakes.
is generally accepted as having been wet-based at that time. What is critical in this model of sub-glacial flow is whether a channel with sufficient hydraulic conductivity could have been generated along the proposed path where the ice thickened northward to the Syracuse area and thinned eastward to the Mohawk valley outlet. The maximum ice thickness along this path during this time of rapid ice retreat was significantly less than the 1000m figure reached by Ridky and Bindschadler (1990) at the time of the Valley Heads advance. That sub-glacial channels can exist under an ice thickness of up to 1000m is documented by observations in Greenland, where supra-glacial and ice marginal lakes drain into sub-glacial channels (Das, et al., 2008; Sarah Das, pers. comm., 2014).

One argument against sub-glacial flow into an ice mass is that hydraulic equipotential surfaces for englacial flow dip into the ice with a slope 11x the ice surface slope (e.g. Shreve, 1972). In the ideal situation water would flow through the ice perpendicular to the equipotential surfaces. However, solid ice is effectively impermeable and where water flows in interconnected channels that have ingress and egress to a free (atmospheric) surface the equipotential surface for that system is horizontal. In that case water will flow down a hydraulic gradient with respect to that system regardless of the ice surface slope. Gulley et al. (2012) provide an example in Svalbard of channelized subglacial flow that departs from ideal hydraulic gradients.

The larger problem for the proposed flow path is that, for almost all that path, the pressure of the plastic ice will be greater than the water pressure on the conduit walls. To maintain an open conduit the rate of wall melting must equal or exceed the rate of plastic closure. In the case of the proposed model, conduit maintenance would be implemented by energy dissipation in the moving water and by the supply of relatively warm surface water. It is also possible that, during that time, a sub-glacial lake existed in the Cayuga Trough, in which case channel maintenance would be made easier. Heat transport from surface water sources have been shown to be sufficient to maintain a sub-glacial lake in Greenland where basal ice temperatures are well below the pressure melting point (Willis et al., 2015).

Another question is how this sub-glacial channel could have originated but an example in Norway demonstrates that such channels can occur. There an inland ice sheet, some 70 km in the N-S dimension trapped a large lake in river systems to the north. Water from this lake somehow entered the main river channel beneath the ice mass and exited at the south edge, leading to an extremely large glacial lake outburst flood (Thoresen, 1991; Longva and Thoresen, 1991). Along roughly the first half of this subglacial channel flow had to have been in the opposite direction of the ice surface slope and it is doubtful that this lake provided enough buoyancy to lift the entire ice mass.

It would be extremely unlikely that the proposed sub-glacial drainage would be unique to the Sixmile Trough or be caused by events there alone. Miller (1993) reached a similar conclusion in the Dryden area, that a post-Valley Heads re-advance was followed by drainage into the ice front, stating that “apparently meltwater began to drain through a lower outlet …, across the ice or through a subglacial drainage system…” Sub-glacial drainage might reasonably be expected to have also occurred during this period in the Inlet valley south of Cayuga Lake. An initial search uncovered no lacustrine clays overlying Valley Heads deposits above an elevation of 500’, but instead identified the thick lacustrine section at higher elevations as of Erie Interstade age and beneath a Valley Heads cover. A logical speculation is that this sub-glacial drainage began along the Mohawk/Ontario lowland and propagated into the drainages to the south.

There is little evidence to constrain the nature of ice disappearance in the Sixmile Trough. There are neither kettle-kame areas nor recessional moraines. The only post-till deposits are thin aprons and fans, clearly fed from the adjacent uplands. The bulk of the ice must have been quite clean because no surface highs to the north of the trough existed as sources.
The initiation of a pro-glacial lake in the Sixmile Trough at about an 800’ elevation, implies that the sub-glacial channel must have closed. The lacustrine silt and fine sand directly overlying till in the Sixmile Trough indicates a rapid inundation, which would have resulted from such a closure.

It is difficult to assess how far the ice front retreated before the sub-glacial channel closed and how the subsequent lake fits with the accepted history of regional pro-glacial lakes. An 800’ elevation would roughly correlate with the interfluve elevation of the Mapleton moraine with differential rebound, using an extrapolated exponential curve applied to the data of Pair and Rodrigues (1993). Bird & Kozlowski (2014) associate the Mapleton moraine with Lake Hall, for which Fairchild (1934) has an elevation at Ithaca of 825’. Fairchild has a Lake Warren level at Ithaca at 795’ but Bird and Kozlowski associate Lake Warren with the Waterloo moraine.

This series of proglacial lakes was responsible for the lacustrine sediments in the lower Sixmile Trough, both in the terraces along the stream and in the subsurface beneath the Ithaca fan. The sediments in the boreholes are thin-bedded silts and clays similar to those drilled in the Inlet (a hollow stem auger hole drilled on Cecil Malone St. for and logged by the author) and imaged seismically. The pro-glacial lake sequence terminated with the sudden drop in elevation of Lake Iroquois at 11.7 ka (Anderson and Lewis, 2012; and references therein), which led to the formation of Cayuga Lake as a separate water body and to a significant drop in base level of streams entering this lake. This led to erosion and incision of the lacustrine strata, followed by deposition of a sheet of fluvial sand and gravel and to the formation of the Ithaca fan. By this time the Sixmile watershed was controlled entirely by fluvial processes and the glacial history of the Sixmile watershed had come to an end.

The proposed deglaciation model, with a period of sub-glacial drainage, must explain observations in the Cayuga region that have often been cited to support a 980’ Lake Ithaca. Although Tarr and other earlier workers were remarkably observant and had the advantage of seeing a largely deforested landscape, their work was largely of a reconnaissance nature and tended to emphasize the occurrence of moraines, deltas and lacustrine clays. For example, the features along the northeast side of the Sixmile valley, interpreted by Tarr (Williams et al., 1909) as deltas, were, based on pits and other excavations, interpreted in this study as aprons and fans.

The most commonly cited observations in support of the high level pro-glacial lakes are hanging deltas along the sides of the Cayuga trough (e.g. Williams et al., 1909; von Engeln, 1961), although attempts to correlate these with the proposed pro-glacial lake levels have been less than satisfactory. The terraces along Coy Glen, at the southwest edge of Ithaca, are the clearest examples of hanging deltas and the terraces below about 800’ appear on the 2’ Lidar topography to be deltaic. Moreover, gravel mining in some of these features exposed well-developed foresets (Garrett, 1960). However, above 800’ the few terrace-like features do not have flat tops and could easily be alluvial fans.

Chisnell (1951) presented convoluted and unconvincing evidence for pro-glacial lake strand lines and delta tops in the Cayuga region to elevations of more than 1000’ but recognized much less development above about 800. Tarr’s (Williams et al, 1909) review of deltas in this region, compared with observations made during this study leads to the supposition that many more deposits of sand and gravel were interpreted as deltaic than was warranted.

Lacustrine silt and clay, mapped on the east side of the Cornell campus (Williams et al., 1909) at an elevation of about 800’, were identified as deposits in Lake Ithaca. A clear exposure of this section was created when Judd Falls Rd was realigned and showed that these were ice-contact sediments in intimate association with till. It seems more likely that these sediments were deposited in a small ice marginal lake rather than in a large pro-glacial
Lake Ithaca. Borehole logs (CHA & Associates, 2007) and trench examination of a natural gas pipeline excavation between Elis Hollow and the Cornell central heating plant, which traverses an adjacent area that was mapped by Tarr (Williams et al., 1909) as lacustrine, revealed only till, much of which was extremely clay rich, and might be mistaken for lacustrine deposit.

Still to be explained in the subglacial drainage model are the moraines delineated by Lidar imagery north of Fall Creek (Fig. 23) that would have been created during the period of sub-glacial drainage. The question is whether the halts or minor re-advances of the ice front are compatible with an open sub-glacial conduit because the moraines imply conditions that would tend to close the conduit. One possibility is that the sub-glacial drainage was intermittent, with short closure periods when the moraines were formed. It might also be speculated that ephemeral lakes would develop during closure and lead to glacial lake outburst floods during openings.

CONCLUSIONS
This study confirms most of the observations made in the Sixmile watershed a century ago but new approaches, such as seismic techniques and Lidar, as well as much more drilling and chronologic information, have added substantially to the objective knowledge of its Quaternary history. In particular, these observations show that the deglaciation history since the Valley Heads advance is much more complicated than heretofore envisaged.

The conclusions reached in this study are based on field observations and some of those conclusions differ radically from those of the generally accepted model. The most radical differences concern the existence and nature of the pro-glacial lakes. The earlier model logically followed from the assumption that the ice front acted as a dam, and that lake levels could be determined from the topography, corrected for post-glacial rebound. Observations made during this study have cast the assumption that the ice was always a dam into serious doubt and has presented data supporting sub-glacial drainage for a period of time. The sub-glacial drainage model remains very speculative, but there are too many problems with the older model not to raise serious questions concerning its validity.

The most surprising conclusion reached in this study was how much is yet to be discovered concerning the Quaternary history of the Cayuga area.

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