

Anatomy of a Crevasse Fill Ridge In Clara's Woods, Stony Brook, New York

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Introduction

Clara's Woods, located on the Stony Brook University campus near the north shore of Long Island, contains a well-developed north-south trending asymmetrical ridge approximately 7 meters high. It is theorized that this ridge was formed in a crevasse at the front of Laurentide ice sheet during the advance that created the Harbor Hill Moraine. Ground Penetrating Radar surveys and Electrical Resistivity surveys conducted along a transect of the ridge show subsurface geologic characteristics consistent with this theory of formation.

Background

Review of Crevasse-Related Landforms

Glacial crevasses, or fractures, are the result of brittle failure which occurs when glacial ice cannot creep fast enough to allow the glacier to adjust its shape under stress (Benn and Evans, 1998). Such fractures are thought to be created during phases of active ice movement, as observed in present day surging glaciers (e.g. Morawski, 2005; Sharp, 1985). These may occur at the glacier's base (basal), on the glacier's surface (supraglacial), or extending the entire ice thickness (Benn and Evans, 1998), depending on the local conditions of both the glacier and the underlying surface.

These crevasses are subsequently widened during stagnation of the ice sheet and then filled with sediment during the early part of the quiescent phase. As the glacier sinks into its bed, basal crevasses may be filled with subglacial material, if the material has an elevated pore fluid pressure. This fluid pressure allows the material to be squeezed up into the crevasses in response to the pressure gradient that exists between sediment overlain by glacier ice and unconfined sediment on the glacier foreland or beneath low pressure cavities (Benn and Evans, 1998). Supraglacial crevasses conversely, are filled with morainic sediment derived from the glacier's surface during ablation (Flint, 1928; Morawski, 2005). Crevasses which penetrate the entire ice thickness, may fill with both subglacial and supraglacial sediment.

Due to the nearly-vertical nature of crevasse walls, ridge landforms created within the crevasses tend to have steep slope angles (Sharp, 1985) and typically stand an average of 5 meters in height, but can be smaller or larger depending on local conditions. Melting of the ice surrounding the crevasse saturates the ridge sediments, leading to failure and resulting in mantles of flowed sediment surrounding the ridge (Sharp, 1985). Such melting also leads to deposition of material frozen within the base of the ice, thus creating a mantle of sediment. In some locations, the mantle is created by the let-down of supraglacial material on top of ridge sediments (Benn

and Evans, 1998), which may cause such ridges to disappear, especially where they lie adjacent to end moraines (Stewart *et al.*, 1988).

Few studies have focused directly on the landforms associated with the infilling of glacial crevasses, however those that have, used a variety of terms to describe such landforms. “Crevasse fill,” “crevasse filling,” and “crevasse infill” have all been used to denote landforms of both basal and supraglacial origins (e.g. Flint, 1928; Sharp, 1985; Hart *et al.*, 1991), whereas “crevasse intrusion,” “crevasse diaper,” and “crevasse squeeze ridge,” have been used only to denote landforms of basal origin (e.g. Boulton *et al.*, 1996; Bennett *et al.*, 2003; Evans *et al.*, 1999) which necessitate deforming bed conditions. For the purpose of this paper, the terms “crevasse fill” and “crevasse squeeze ridge” will be used accordingly.

Basal crevasse fill ridges have been reported from a number of recently deglaciated glacier forelands (Hoppe, 1952; Okko, 1955; Mackay, 1960; Galon, 1973; Mickelson and Berkson, 1974; Haselton, 1979; Clark *et al.*, 1984), however the most thorough study was conducted by Sharp (1985), who examined recently exposed examples from the foreland of an Icelandic surging glacier.

Basal crevasse squeeze ridges have been found to occur in sequence with patchy hummocky moraine containing kettle holes, zones of thrust moraine, and proglacial outwash (Evans *et al.*, 1999). In order for this landform assemblage to form, the following conditions must exist: 1) a glacial advance which produces compression in weakly consolidated or discontinuously permafrozen subglacial sediments, leading to the formation of thrust moraine; 2) stagnation and sinking of the glacier into its bed, causing subglacial sediments to be squeezed into basal crevasses; 3) debris derived from the glacier bed and transported to englacial and supraglacial positions along shear planes within the glacier must melt-out, forming the topographic high mounds characteristic of hummocky terrain; 4) stagnant buried ice blocks must melt, causing the subsidence typical of kettle holes; and 5) the water derived from the melting glacier must be expelled, causing deposition of sediments from the adjacent moraine in the form of an outwash plain.

To date, crevasse fill ridges have not been explicitly identified on Long Island; however other studies conducted near Stony Brook University have confirmed the presence of landforms which often occur in conjunction with crevasse fill ridges. This suggests that favorable conditions existed locally for their formation during the last glaciation.

Long Island Geology

The geology of Long Island is dominated by two push moraines, trending in a general east-west orientation: the Ronkonkoma Moraine, which spans the center of the island, and the Harbor Hill Moraine, which runs along the north shore (Fig. 1a). Clara’s Woods is located on the south campus of Stony Brook University, on a segment of the Harbor Hill Moraine that is commonly referred to as the Stony Brook Moraine (Fig. 1b & 1c).

The arcuate shape of the Stony Brook Moraine, like other push moraines, was created by the pushing of unconsolidated sediments in front of a glacier, as described by Tzakas *et al.* (2002). This pushing, from north to south, formed a multi-crested thrust moraine complex. Nienstedt and Hanson (2004) studied the stratigraphy of these moraine sediments beneath the Stony Brook University campus, finding that they consist dominantly of glacial sands and gravels which are underlain, in some areas, by a unit known as the Smithtown Clay.

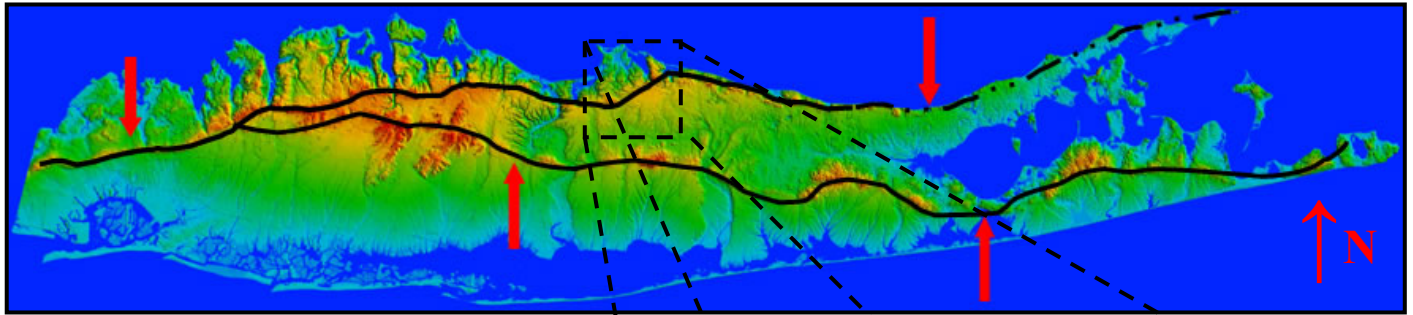
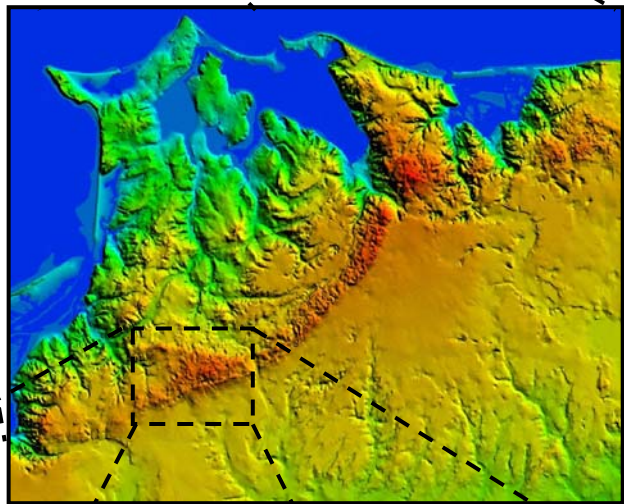


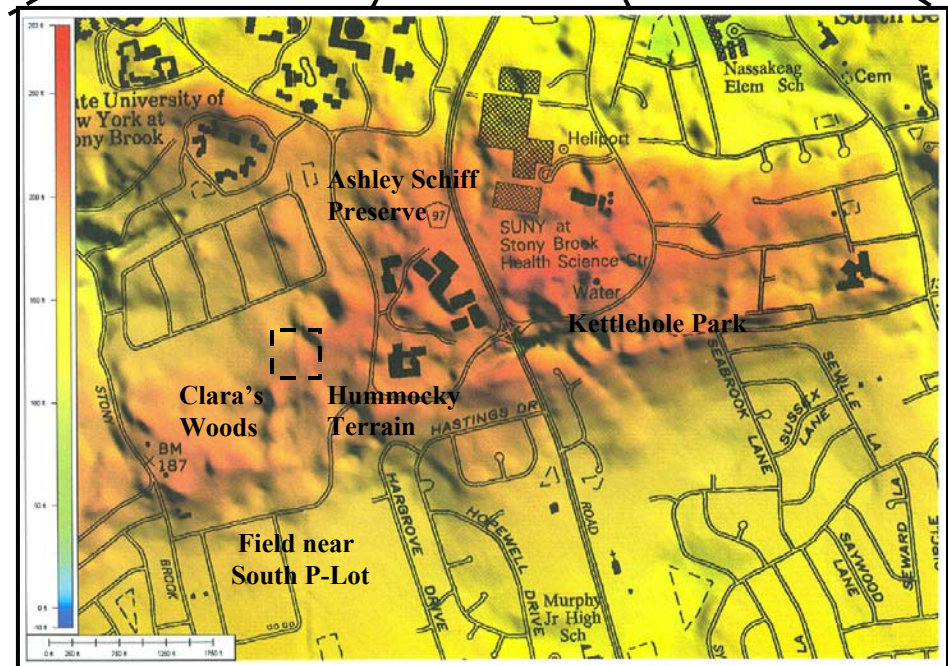
Figure 1. DEM of GPR and resistivity study area in Clara's Woods.

a) (top right) A DEM of Long Island indicating the location of the moraines. The arrows pointing down indicate the Harbor Hill Moraine, and the arrows pointing up indicate the Ronkonkoma Moraine. The rectangle indicates the area of (b).



b) (center right) A DEM of the Stony Brook Moraine, showing the effects of glacial processes on local landforms and topography. The rectangle indicates the area of (c).

c) (bottom right) A DEM of Stony Brook University South Campus and Health Science Center area, indicating the location of Clara's Woods. The rectangle indicates the ridge where GPR and resistivity studies were conducted. The location of the Ashley Schiff Preserve, and the field near the South P-Lot studied by Tingue *et al.* (2004), are also indicated, as well as the locations of Kettlehole Park, studied by Wade *et al.* (1990), and the hummocky terrain identified by Hanson (2004).



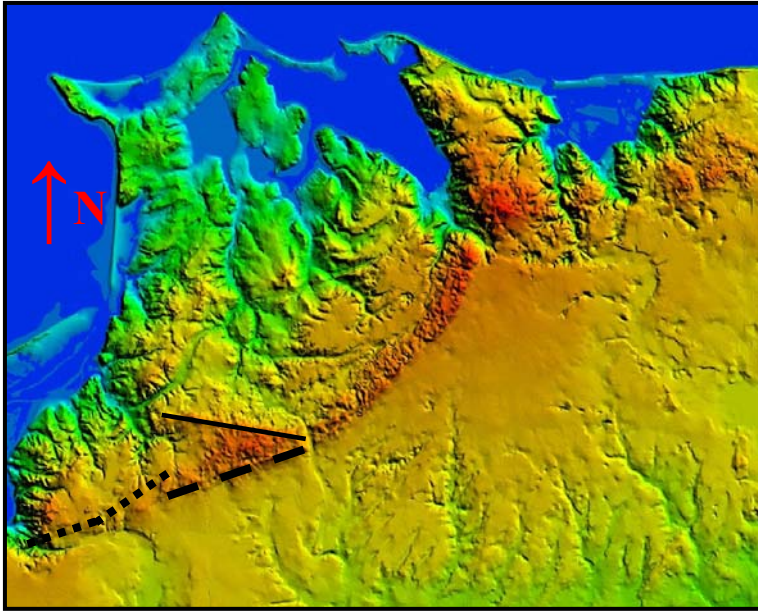


Figure 2. (above) A DEM showing the three segments that comprise the Stony Brook Moraine. The dashed line represents Moraine 1, the dotted line represents Moraine 2, and the solid line represents Moraine 3 (Hanson, 2004).

Hanson (2004) analyzed Digital Elevation Maps (DEMs) of the Stony Brook Moraine and concluded that it is the product of three distinct ice-lobe advances and retreats. He proposed that the glacial history of the area included the advance of the Stony Brook glacial sub-lobe which formed an arcuate push moraine (Moraine 1 in Fig. 2), followed by an advance of the Harbor Hill glacial lobe (Moraine 2 in Fig. 2), and finally a re-advance of the Stony Brook sub-lobe, forming a second push moraine (Moraine 3 in Fig. 2) at approximately the same position as the push moraine from the first advance.

Ground Penetrating Radar (GPR) surveys conducted by Tingue *et al.* (2004) in the Ashley Schiff Preserve, located on the Stony Brook University campus near Clara's Woods (Fig. 1c), revealed compressional features typical of fold and thrust terrain, confirming the influence of proglacial deformation on the area. In addition, evidence suggests the presence of truncated stratigraphic layers, and a cobble-rich upper stratigraphic layer, signifying the influence of subglacial deformation processes in this area.

Based on observations of topography consisting of irregular mounds of till with intervening topographic depressions, or kettle holes, Hanson (2004, personal communication) believes that the area south of the Ashley Schiff Preserve and surrounding the South Entrance to Stony Brook University (Fig. 1c) is hummocky terrain. The Harvey Kettle Hole formation in Kettlehole Park, located just south of the Stony Brook Health Science Center (Fig. 1c), is positioned near the moraine's southern-most extent, and is therefore considered a morainal kettle (Wade *et al.*, 1990). Kettles such as this signify areas of subsidence caused by the melting of stagnant buried ice blocks and are formed along with the associated topographic high mounds of till that make up the terrain.

Such terrain is classically interpreted as the end product of the differential ablation and topographic inversion processes that occur during glacial retreat (e.g. Benn and Evans, 1998). An alternative interpretation presented by Stalker (1960) and later tested by Boone and Eyles (2001), considers some regions of hummocky terrain to be the result of subglacial ice pressing and mobilization of water-saturated, fine-grained substratum, due to variations in overburden pressure which result from corresponding lateral variations in ice thickness. This alternative interpretation necessitates similar conditions and processes as those required for the formation of crevasse-squeeze ridges, therefore implying that such ridges may for the basis for some areas of hummocky terrain.

GPR surveys were also conducted by Tingue *et al.* (2004) in a field just south of the Stony Brook Moraine, near Stony Brook University's South P-Lot, within 1 kilometer of the Ashley Schiff Preserve and Clara's Woods (Fig. 1c). This data indicated a subsurface with nearly layer-cake geometry, and only slight undulations, which are attributed to the chaotic deposition of sediments from the adjacent moraine as water rapidly expelled from the glacier itself, forming an outwash plain. A large number of boulders and cobbles both near the surface and at greater depths were also shown. Those near the surface were suggested to be the result of the advance of the glacier that formed the moraine, while those at greater depths were said to have been deposited by an earlier ice advance.

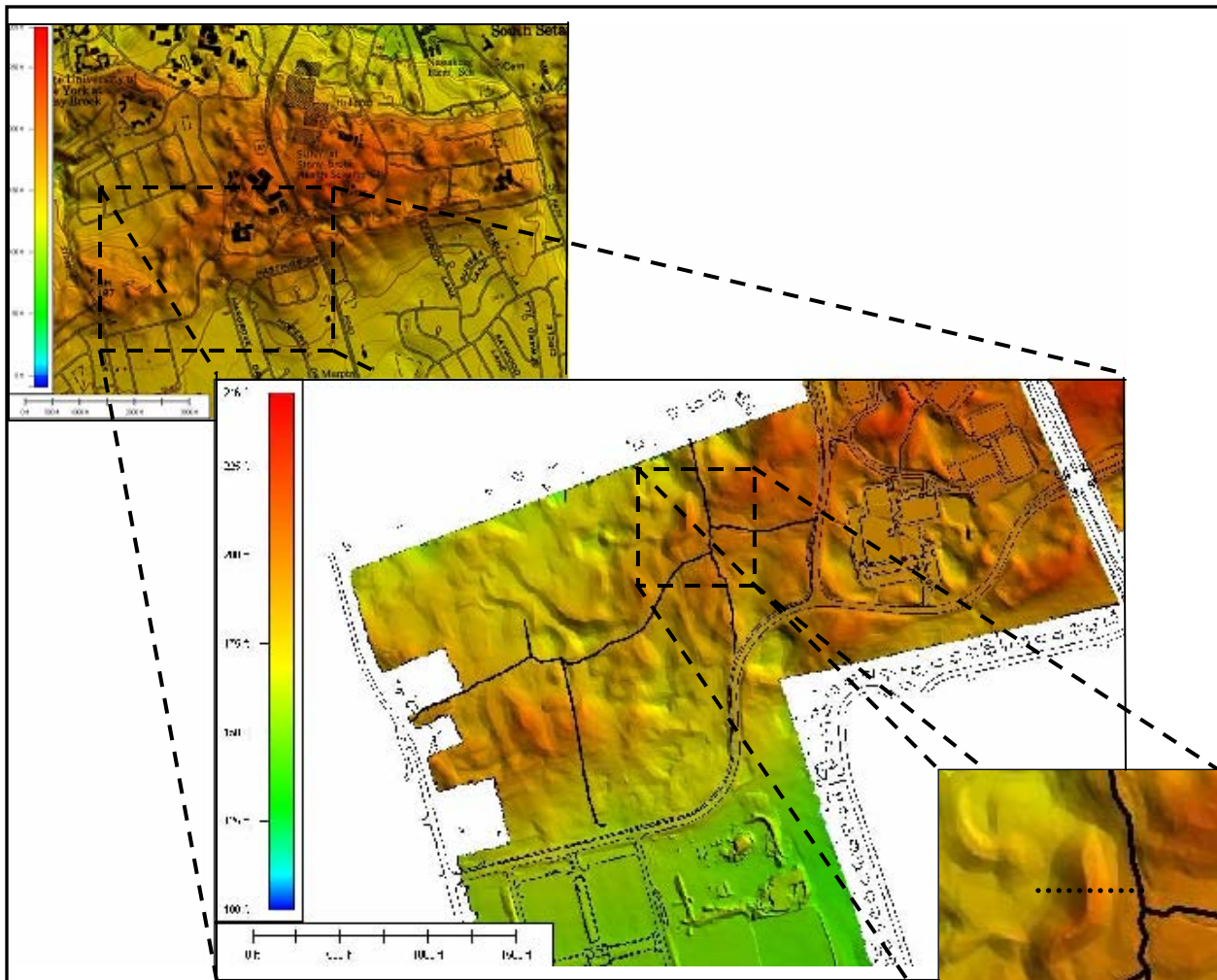


Figure 3. DEM of the Clara's Woods ridge where GPR and Resistivity surveys were conducted. a.) (above right) DEM of the Stony Brook University South Campus. The rectangle indicates the approximate area of b. b.) (above center) DEM of Clara's Woods based on a 2 foot contour interval map with 1 meter spacing. The rectangle indicates the area of c. c.) (above left) Enlarged DEM of the study ridge including a dotted east-west line which represents the approximate location of the ridge transect.

The previous research conducted on the areas surrounding Clara's Woods is essential to understanding the glacial processes that formed the moraine and its features (e.g. fold and thrust terrain, hummocky terrain, kettle holes, proglacial outwash), including the north-south trending ridge in Clara's Woods. These studies confirm that conditions such as north-south oriented compression, stagnant ice, water-saturated substratum, and a cover of supraglacial sediments existed in the area, further suggesting the likelihood that crevasse-related landforms may also be present within the topography, since such conditions are conducive to their formation. This study investigates the internal structure and composition of an east-west transect of one landform (Fig. 3), in an effort to identify the process or processes, which produced this topographic feature.

Methods

In order to understand the geologic processes that formed the north-south trending ridge in Clara's Woods, the topography of the ridge and the geologic characteristics of its subsurface were examined. A topographic profile of the ridge was created by measuring the changes in relief across an east-west transect using a differential leveling technique described by Integrated Publishing (2004). This profile was then used to assist in examining and interpreting the subsurface through Ground Penetrating Radar and Electrical Resistivity.

Ground Penetrating Radar

GPR is a geophysical imaging technique that uses electromagnetic waves to produce a cross-section of subsurface structures. A GPR system uses a transmitting antenna to emit electromagnetic waves into the ground, and a receiving antenna to record reflections of those waves as they encounter changes in the electric and/or magnetic properties of the subsurface material (van der Kruk *et al*, 1997) (Fig. 4). The reflected waves are recorded as distance vs. time, where the time is recorded as the total time elapsed from initial transmission to reception. Each returning wave is defined as a separate trace in the data collection process, and each trace consists of a series of polarities and amplitudes for a certain x-coordinate as a function of depth, digitally recorded as a series of samples in a time sequence (Tingue *et al*, 2004). By moving the transmitting and receiving antennas in tandem along a line, many (hundreds to thousands) traces can be added to create a radargram, a 2-dimensional analogy of the subsurface (Goetz and Davis, 2004; Hubbard *et al.*, 2002).

The image produced by the GPR system indicates stratigraphic layers as layers in the data; however objects embedded in the subsurface, such as boulders, are indicated in the data by hyperbola (Davis, 2002). The hyperbolas represent diffraction signals that are created as the result of the direct relationship between the travel time of the wave and the proximity of the radar system to the object. When the radar system is farther away from the object, it takes a longer time for the wave to travel from the transmitter to the object and back to the receiver, whereas when the radar system is directly over the object, the wave travel-time is shortest. The data from these hyperbolic events can be used to determine the velocity of the transmitted and reflected wave, the depth of a layer or object in the subsurface, and the general composition and density of the layering (Tingue *et al*, 2004; Davis, 2002).

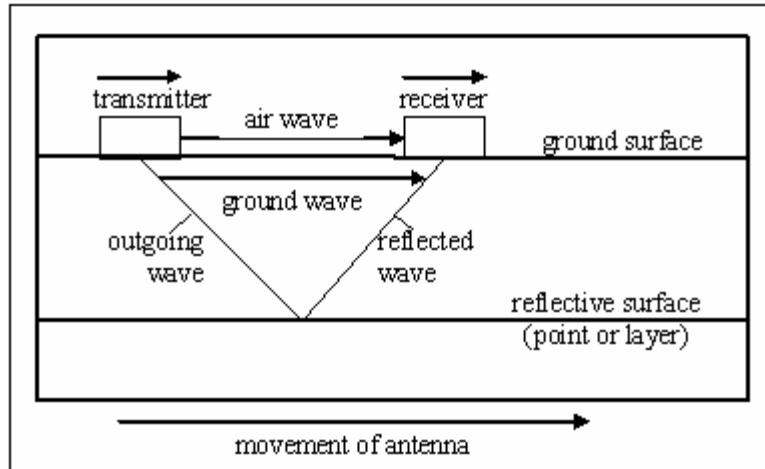


Figure 4. Main principles of a GPR system: Data is received when electromagnetic waves originating from the transmitter reflect off of an object and reach the receiver (after Hubbard et al, 2002).

The frequencies of the antennas typically used for GPR studies range from 20 MHz to 800 MHz, with lower frequency antennas providing less attenuation (loss of signal energy) and allowing for greater penetrating power, while higher frequencies (500 MHz or greater) have greater attenuation and less penetrating power. Thus, lower frequency antennas can detect boulders and coarse-scale layering at relatively great depths (up to a few 10s of meters), while high-frequency antennas can detect cobbles and

finer-scale layering undetectable at low frequencies, but only to shallow depths (typically several meters) (Davis, 2008).

For the purposes of the Clara's Woods study, 200 MHz, 500 MHz, and 800 MHz antennas were used, since they would provide a range of subsurface information incorporating both deep layering patterns and shallow composition information. The 200 MHz antennas were connected to a control unit and a laptop computer strapped to one operator, while another operator placed the antennas at specified increments along the survey line. The 500 MHz and 800 MHz antennas, which are smaller and contained in a single unit, were connected to the laptop computer and transported along the same survey line using a push cart. For both methods, RAMPAC[®] Groundvision GPR Software was used, and 100-meter measuring tapes were laid out along the path of the survey line, corresponding with the points used for collecting topographic data.

The raw data collected from each of the antenna frequencies required a series of processing steps before it could be used for geological analysis. The radar data was processed using Reflexw[®], a program that contains a wide variety of processing filters and functions for interpreting seismic and GPR data. The Reflexw program also has the capacity for incorporating topographic data, allowing for the geophysical data to be viewed in relation to the topography of the study area. Following processing, the data for each antenna frequency was analyzed.

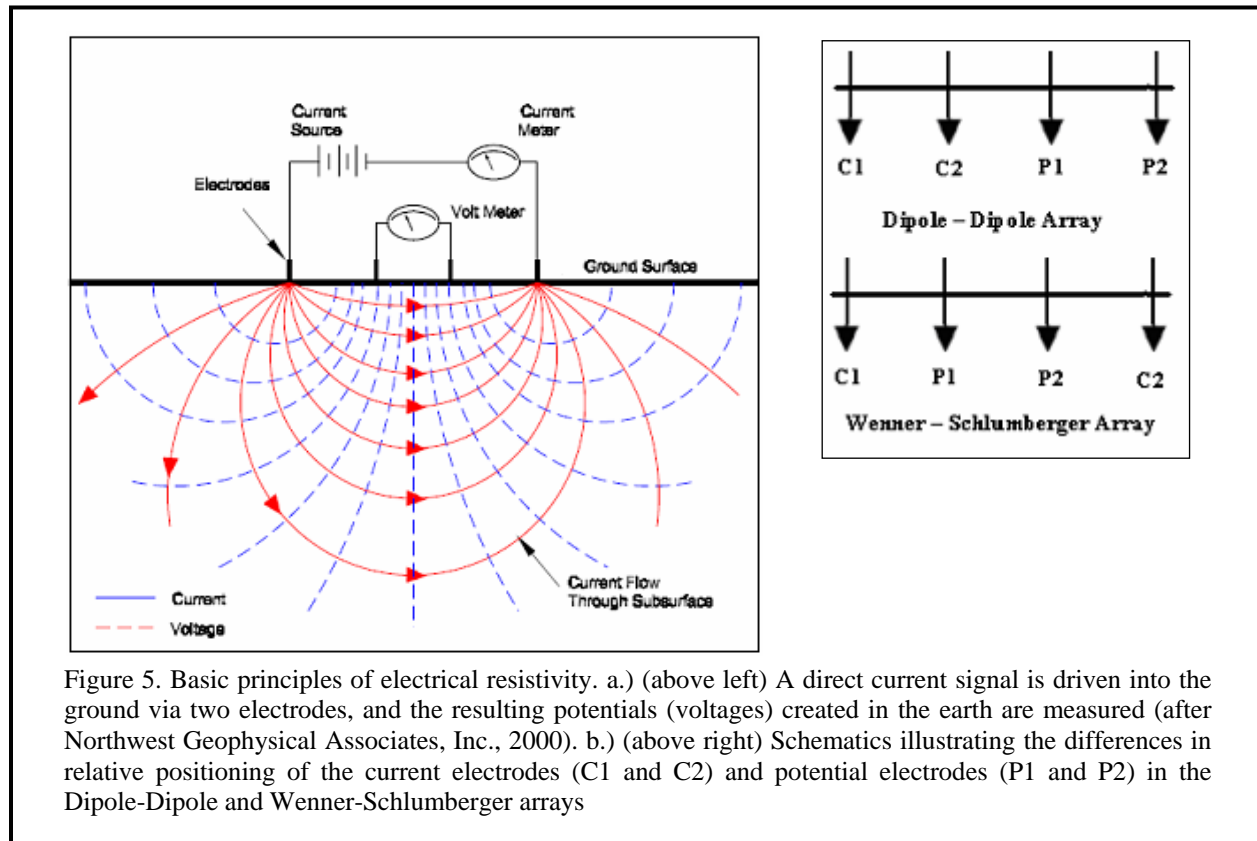
Electrical Resistivity

In order to further study the geologic characteristics of the subsurface, electrical resistivity, a technique that uses electrical current to produce a two-dimensional cross-section of the resistance characteristics of the subsurface materials, was also used. Resistance is the ability of a material to inhibit an electrical current; it is the reciprocal of electrical conductivity.

Electrical resistivity uses a linear array of metal electrodes, inserted into the ground at regular spacing, and connected by an insulating cable to a current source and voltmeter. These electrodes are used in combinations of four, known as quadrupoles, to take measurements. In each quadrupole, two electrodes deliver current into the ground, while the other two electrodes

measure the voltage differences that result as the current passes through the subsurface geologic material, which acts as a series of natural resistors within the direct current circuit (Fig. 5a). In this way, electrical resistivity surveys are able to detect changes in the electrical field and determine the locations, depths, and thicknesses of geologic materials (Lewis, 2003).

The type of linear array used, either the Dipole-Dipole array or the Wenner-Schlumberger array, determines which electrodes inject the current and which measure the resultant voltage. In the Dipole-Dipole array, the pair of current electrodes and the pair of potential electrodes are located adjacent to each other at opposing ends of the quadrupole, while in the Wenner-Schlumberger array, the current electrodes flank the interior pair of potential electrodes (Fig. 5b).



In order to produce a cross-section using either array, a potential is measured across two potential electrodes while current is sent into the ground through a pair of current electrodes. Such potential differences are measured using all possible quadrupole combinations, ensuring that there are varied distances separating the electrode pairs. These varied distances are essential, as the depth measured by the investigation is a function of the electrode spacing, such that the short offsets observe the shallow subsurface, while the longer offsets observe greater depths.

Depending on the quadrupole geometry, each measured potential difference translates to a calculated apparent resistivity. When enough apparent resistivities are amassed, it becomes possible to develop a model for a subsurface with variable resistivity that matches (within acceptable error) all of the apparent resistivities determined for the several quadrupoles in the survey.

The specific resistivity magnitudes obtained however, are not as diagnostic as the spatial distribution of the data, since geologic materials do not have unique, characteristic resistivities.

Alternatively, the spatial variations in the data can be inferred as geologic boundaries caused by changes in lithology, sediment grain size, moisture content, or water chemistry, and thus provide information regarding the distribution of stratigraphy or sediment facies (Lewis, 2003).

For the purposes of the Clara's Woods study, both the Dipole-Dipole and Werner-Schlumberger arrays were utilized along portions of the same survey line. For the Dipole-Dipole study, 47 electrodes were spaced at 1-meter intervals, over a distance of 47 meters, providing a detailed view of the shallow subsurface. The electrodes used in the Werner-Schlumberger study were spaced at 2-meter intervals, over a distance of 94-meters, providing a deeper view of the general subsurface layering, over a greater lateral extent.

The raw data collected from each of the studies were inverted using a finite element technique that allows for the determination of a distribution of electrical resistivity at depths capable of best explaining the measured voltages (Davis, 2002). Following processing, the data for each array was analyzed and compared to the data obtained from the GPR surveys.

Analysis

GPR

The 800 MHz and 500 MHz radargrams (Fig. 6) show approximately 5 meters of the subsurface over a distance of approximately 75 meters. Both are replete with hyperbolic reflectors, which are identified by diffraction hyperbola (frowns) in the data. These hyperbolas are so numerous that they overlap one another, indicating a geologic material comprised of many closely spaced clasts, which are large enough to be resolved at these high frequencies.

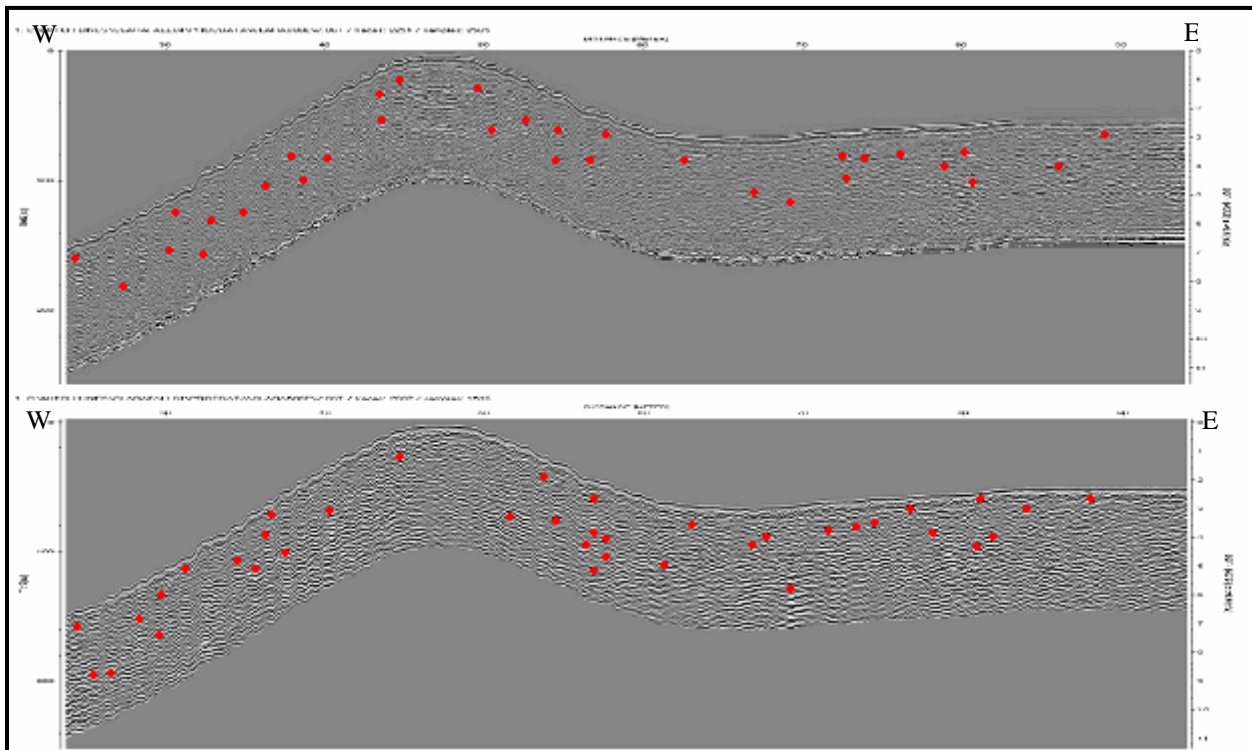
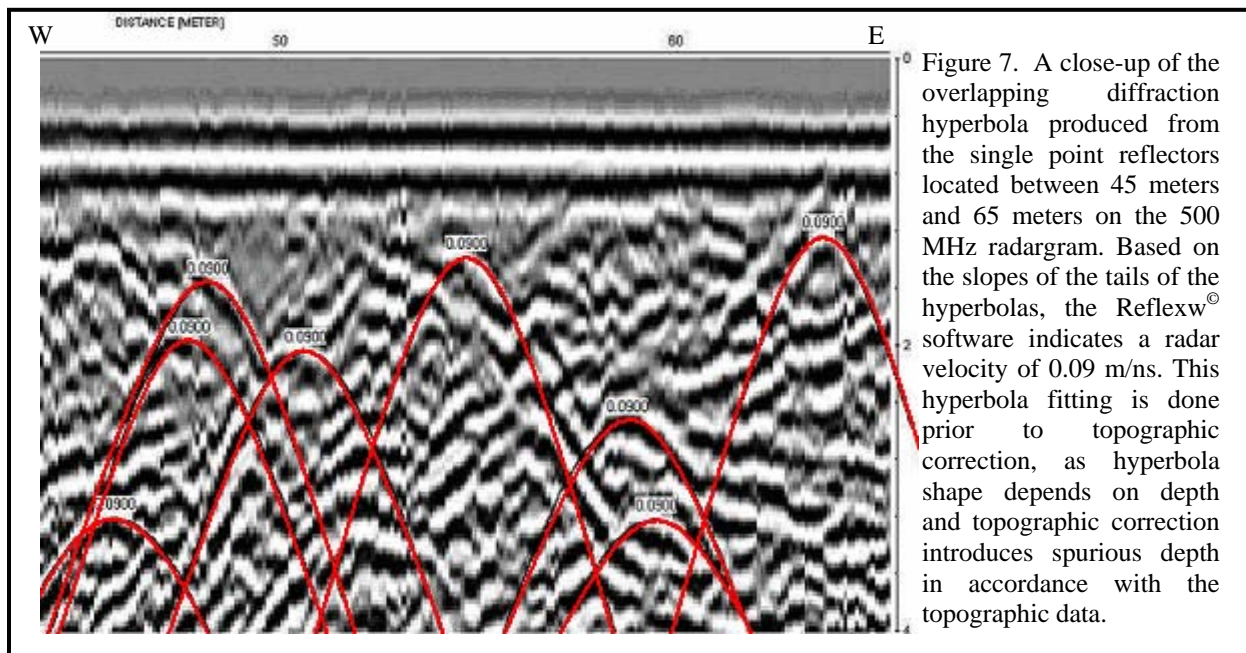


Figure 6. GPR results with topographic correction and a vertical exaggeration of 2:1. Cobbles and boulders, which are indicated by diffraction hyperbola, are annotated by red dots. The gray areas beneath the data indicate the drop-out of data at depth, which is a function of the penetrating power of the antenna. a) (top) 800 MHz radargram with a vertical scale equivalent to about 5 meters, and a horizontal scale of about 75 meters. b) (bottom) 500 MHz radargram with a vertical scale equivalent to about 5 meters, and a horizontal scale of about 75 meters.



Using the slopes of the hyperbolas tails, which are a function of the relationship between the wave travel time and the proximity of the radar system to the individual clasts, the Reflexw[®] software indicates a radar velocity of 0.09 m/ns, or 9 cm/ns (Fig. 7). Radargrams such as this are common in extremely poorly sorted sediments rich in cobbles and boulders, such as glacial till (Davis, 2002).

The 200 MHz radargram (Fig. 8), which shows 15 meters of the subsurface over a distance of 75 meters, also shows the abundance of single point reflectors indicative of glacial till. This illustrates that the till is concentrated on the flanks of the ridge, with a high concentration of diffraction hyperbola appearing east and west of the ridge, very few diffraction hyperbola appearing near the ridge axis, and no diffraction hyperbola appearing in the core of the ridge. Due to the nature of till, stratigraphic layers are difficult to discern in these sediments in the radargram.

Stratigraphic layers, which roughly follow the topography, are however, discernable at shallow depths beneath the ridge axis and continue beneath its eastern slope for a few meters (Fig. 8). Beneath this layering, the core of the ridge appears featureless in the radargram, indicating that it lacks the cobbles and boulders indicative of till, and is devoid of stratigraphic layers. Data from the resistivity study will help to further identify this material.

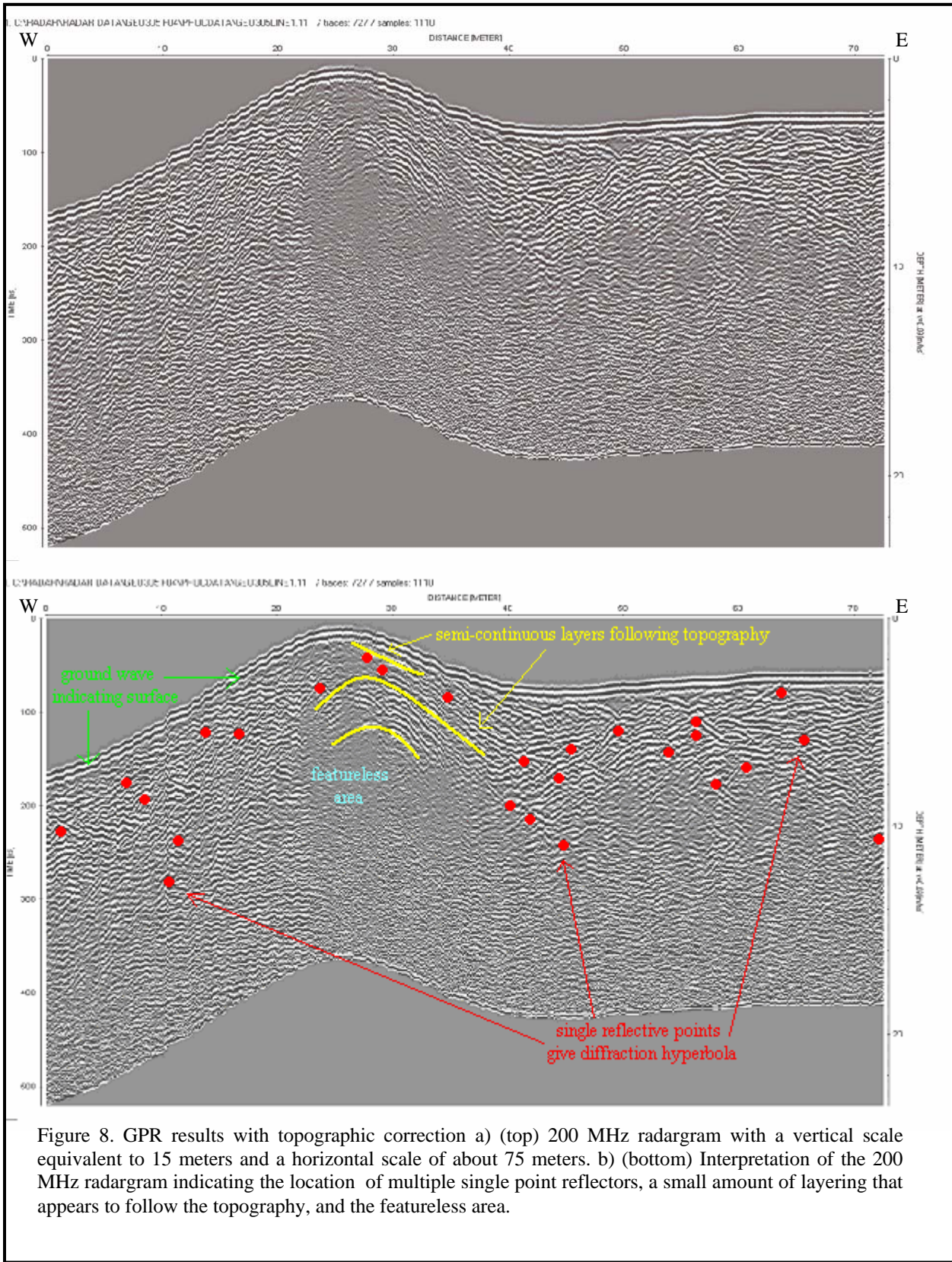
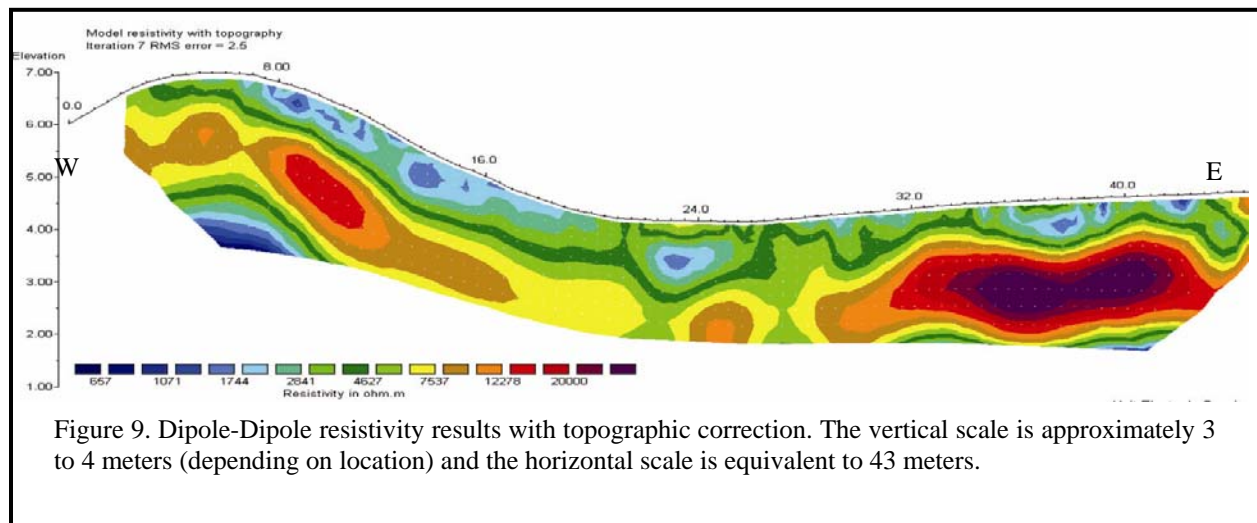


Figure 8. GPR results with topographic correction a) (top) 200 MHz radargram with a vertical scale equivalent to 15 meters and a horizontal scale of about 75 meters. b) (bottom) Interpretation of the 200 MHz radargram indicating the location of multiple single point reflectors, a small amount of layering that appears to follow the topography, and the featureless area.

Resistivity

The Dipole-Dipole resistivity results (Fig. 9) show 3 to 4 meters of the subsurface over a distance approximately 43 meters. The results indicate the presence of a conductive material (indicated by very low resistivity), shown in blue, approximately 3 meters beneath the ridge axis. It also indicates the presence of highly resistive material, indicated in red and purple, flanking the eastern slope of the ridge as well as near the eastern-most extent of the study line. This highly resistive material is 1 to 1 ½ meters thick and is located in the shallow subsurface.

The results also indicate the presence of several small pockets of low resistivity material, shown in blue, at and just below the surface. These pockets are presumed to be the result of variations in local water saturation, rather than changes in geologic material, as water was applied to the surface near several of the electrodes in order ensure proper function.



The Wenner-Schlumberger resistivity results (Fig. 10) provide a deeper subsurface view of approximately 8 meters, over a distance of nearly 85 meters. The results indicate that the core of the ridge is composed of a conductive material (again indicated by very low resistivity), shown in blue, beginning approximately 3 meters below the surface. Based on the similar resistivities and the corresponding depths from the surface, this material is the same as that shown beneath the ridge axis in the Dipole-Dipole study. A second area of low resistivity material, shown in blue, is also indicated toward the eastern end of the study line, approximately 3 meters beneath the surface. The conductive nature of the material in these locations, when considered in context with the geologic setting, indicates that it is clay-rich.

The Wenner-Schlumberger results also show that the flanks of the ridge are composed of highly resistive material, shown in red and purple (Fig. 10). This material varies in thickness from ½ meter near the ridge axis, to 2 meters on the eastern and western sides of the ridge, and generally follows the topography, clearly overlying the conductive clay material. At the eastern base of the ridge (at approximately 68 meters in Fig. 10) this highly conductive material forms a narrow vertically oriented band at least 6 meters thick.

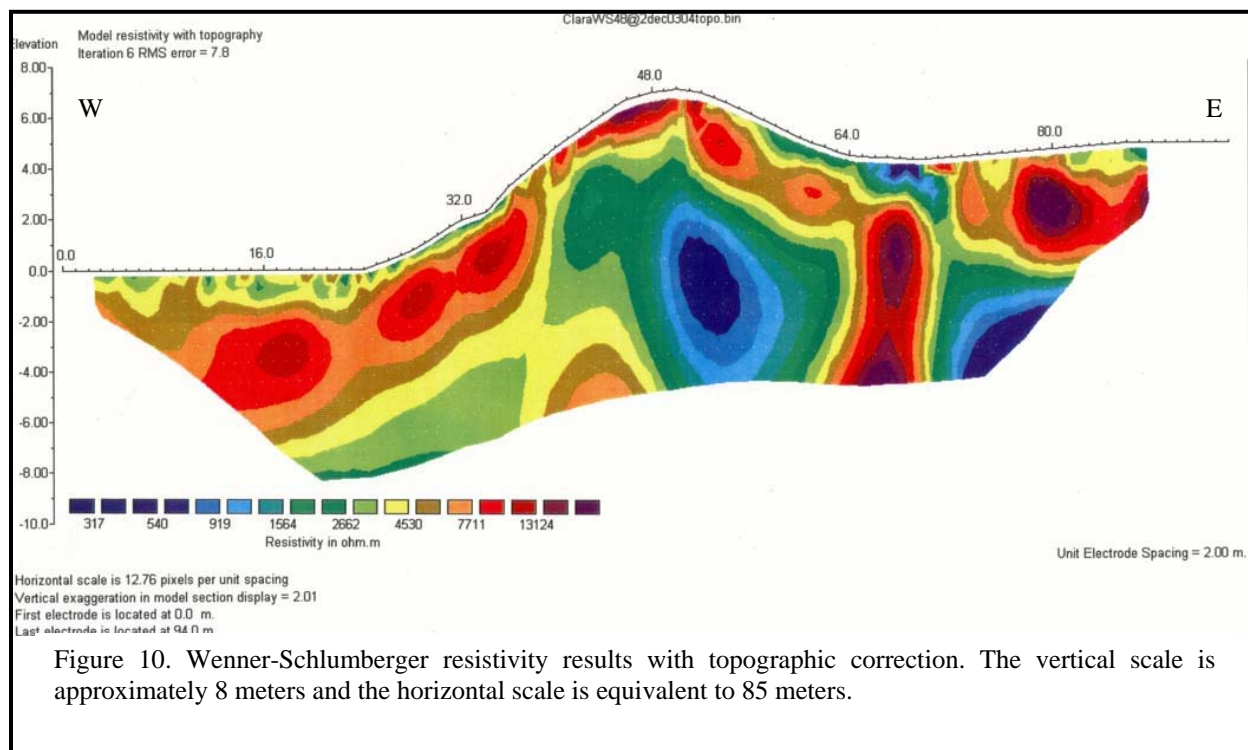


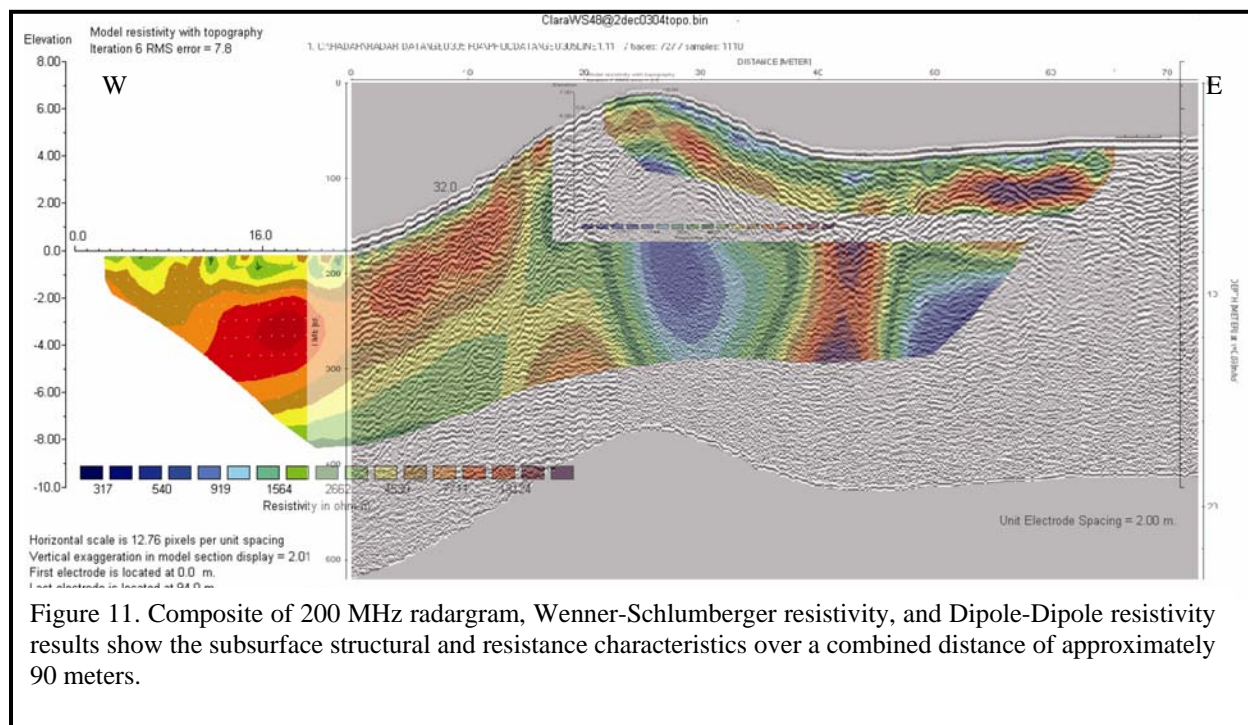
Figure 10. Wenner-Schlumberger resistivity results with topographic correction. The vertical scale is approximately 8 meters and the horizontal scale is equivalent to 85 meters.

Based on the similarities in resistivity and corresponding depths and thicknesses, it is presumed that all of the highly resistive material indicated in the Wenner-Schlumberger survey is the same as the high resistivity material shown along the eastern portion of the study line in the Dipole-Dipole study. The resistive nature of this material, when considered in context with the geologic setting, indicates that this material is glacial till composed of boulders and cobbles.

Composite

Figure 11 is a composite overlay of the 200 MHz radargram, the Wenner-Schlumberger resistivity results, and the Dipole-Dipole resistivity results. By viewing the data together in this manner, the relationship between topography, resistance characteristics, and structural characteristics can be more directly observed, thus providing a better visual of the ridge's subsurface characteristics.

From this composite, it is evident that the low resistivity material at the core of the ridge is the same material that appears featureless in the GPR; a combination of results which indicates that this is a clay-rich material. It is also clear that the high resistivity material on the flanks of the ridge corresponds with the locations of the diffraction hyperbola in the GPR; a combination which may be indicative of glacial till, presuming that boulders and cobbles constitute a large volumetric percentage of the material.



Discussion

The combination of GPR and resistivity indicates that the north-south trending ridge in Clara's Woods is a crevasse fill ridge that formed at the margin of the Laurentide Ice Sheet, during the advance that produced the Harbor Hill Moraine. This ridge is interpreted to consist of a clay-rich core which is conductive (blue) in resistivity and featureless in the GPR. This material is most likely glaciolacustrine in nature and is suspected to be Smithtown Clay. It appears to have high slope angles under the ridge, suggesting that it may have undergone squeeze-type deformation beneath the glacier, thus making it a crevasse squeeze ridge.

Concurrently, the flanks of the ridge are interpreted to consist of glacial till which is resistive (red and purple) in resistivity and appears as diffraction hyperbola in the GPR. Due to the position of the till, along with its variable thickness, it is likely that it was deposited following the subglacial squeezing of the clay. Less clear however, is the type of till comprising the layer. This till may be supraglacial till that infilled the crevasse as the glacier melted, or alternatively it may be subglacial till which resulted from the melt-out and deposition of material lodged in the base of the ice. A subglacial origin for the till could account for the compact nature of the till since dewatering under ice overburden pressure can lead to over-consolidation, whereas a supraglacial till would more likely be less compressed. Although either origin is plausible, most likely this layer is composed of varying proportions of both supraglacial and subglacial till, making it difficult to resolve the balance between the mechanisms for filling of the crevasse from above and below the glacier.

Considering these interpretations, it is probable that the landform is of dual origin and should therefore be characterized as a crevasse fill ridge.

Formation of the Crevasse Fill Ridge and Surrounding Landforms

The Laurentide Ice Sheet advanced from the north, eroding bedrock and transporting this eroded material south. The material was transported subglacially and abraded by the force of the ice into particles ranging in size from boulders to fine sediments. Some of this material was later carried to the englacial and supraglacial environments via thrusting within the ice itself. During the active phase of ice advance, stresses within the ice caused the formation of crevasses with near-vertical walls. Those crevasses which formed closest to the glacial margin, most likely extended throughout the entire ice thickness, as the ice in this region is relatively thin.

As the glacier advanced toward the present-day north-shore of Long Island, the subglacial environment changed from bedrock to the unconsolidated sands and gravels that were previously deposited via the glacial advance that created the Ronkonkoma Moraine. In addition to these glacial sediments, previous research (e.g. Hanson, 2004) suggests that the glacier also encountered the sediments which comprise the Smithtown Clay unit, which is thought to have been created in a pro-glacial lake dammed by the earlier Ronkonkoma Moraine (Krulikas and Koszalka, 1983). The advancing glacier incorporated these unconsolidated sediments and pushed them into the glacial foreland, forming fold and thrust terrain such as that identified in the Ashley Schiff Preserve. Continuing advancement of the glacier over this terrain, led to the truncation of the upper stratigraphic sediment layers.

When the glacier stagnated, it began to melt, saturating the sediments below. In the Clara's Woods study area, the upper layer of these subglacial sediments was clay-rich, possibly resulting from glacial bulldozing and repositioning of the Smithtown Clay. The Smithtown Clay does not typically appear as part of the stratigraphy under the highest parts of the Stony Brook Moraine, such as the Clara's Woods area, and therefore must have been transported there by glacial tectonics (Nienstedt and Hanson, 2004), if the clay identified in the GPR and resistivity is, in fact, Smithtown Clay.

As the glacier sank into these underlying clay-rich sediments, gravitational pressure differences between those areas under the ice and those exposed to atmospheric pressure at the base of the crevasse caused the sediments to become mobilized by fluid and subsequently squeezed into the base of the crevasse (Fig. 12a) thus creating the clay-rich ridge core observed in the GPR and resistivity.

The glacial melting and subsequent sediment saturation led to the expulsion of water and smaller sediments, forming the outwash plain identified by Tzakas *et al.* (2002). As this melting occurred, the crevasse located above Clara's Woods widened, and sediments and boulders in the form of supraglacial till may have collected in the ice-topographic low (Fig. 12b). Further melting would have allowed this material to be let down on top of the subglacially formed clay-rich ridge, forming a mantle on the flanks of the ridge, thus producing a sediment-topographic high (Fig. 12c) containing the boulders and clay-rich areas revealed by the GPR and resistivity.

Alternatively, as the melting occurred, sediments and boulders encapsulated within the subglacial environment, may have been let down on top of the flanks of the clay-rich ridge, in the form of compact subglacial till (Fig. 13a), thus forming a sediment-topographic high (Fig. 13b and 13c). Most likely, some combination of these two processes occurred, depositing both supraglacial and subglacial till on the flanks of the clay-rich ridge.

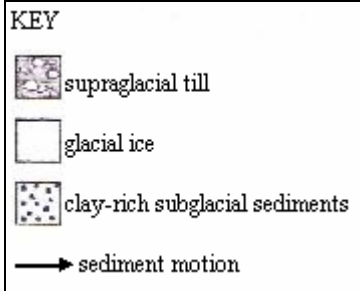
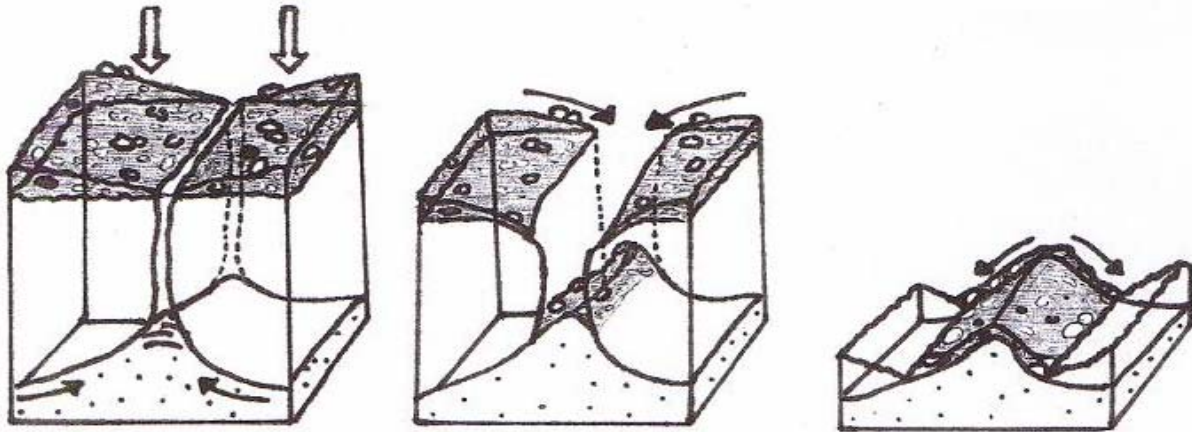


Figure 12. 3D-schematic of the formation of the Clara's Woods crevasse fill ridge with supraglacial till a) (top left) The stagnant debris covered glacier sinks into clay-rich subglacial sediments, squeezing the sediments into the base of the crevasse, forming a crevasse squeeze ridge. (Note: The arrows appearing above the figure represent the force of gravity acting on the glacier.) b) (top center) Melting of the glacier causes the crevasse to widen, therefore causing backwasting and the collection of supraglacial till within the crevasse. c) (top right) Further glacial melting causes the supraglacial till to blanket the clay-rich ridge, and continued backwasting causes the till to concentrate on the flanks of the ridge, thus creating the sediment-topographic high crevasse fill ridge.

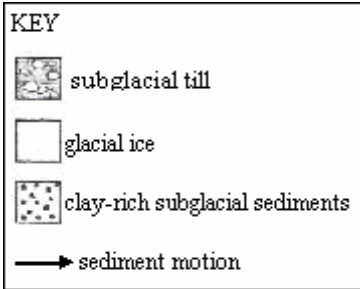
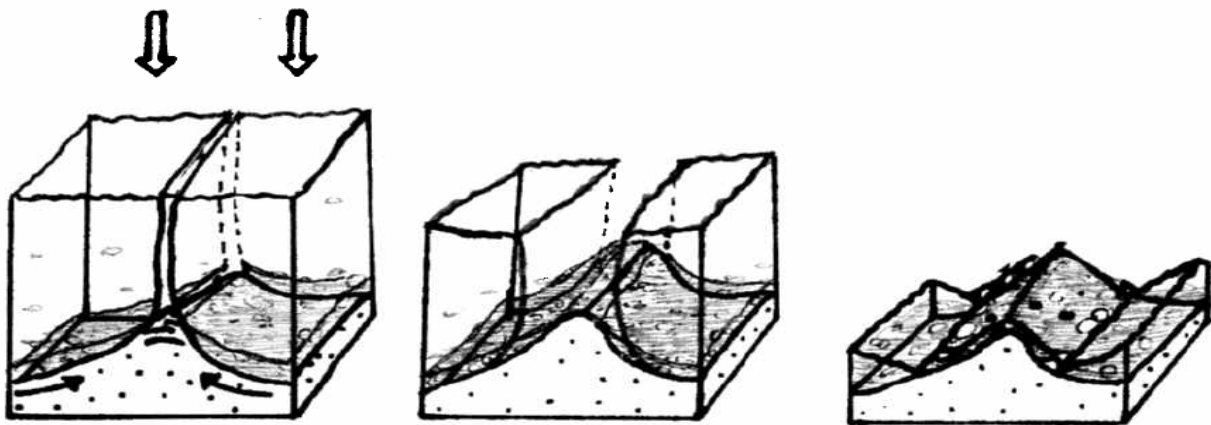


Figure 13. 3D-schematic of the formation of the Clara's Woods crevasse fill ridge with subglacial till a) (top left) The stagnant glacier sinks into clay-rich subglacial sediments, squeezing the sediments into the base of the crevasse, forming a crevasse squeeze ridge. The subglacial till remains frozen within the base of the glacier. (Note: The arrows appearing above the figure represent the force of gravity acting on the glacier.) b) (top center) Melting of the glacier causes the crevasse to widen, and causes the deposition of the subglacial till on top of the clay-rich sediments. c) (top right) Further glacial melting causes the subglacial till to blanket the clay-rich ridge, and backwasting causes the till to concentrate on the flanks of the ridge, thus creating the sediment-topographic high crevasse fill ridge.

While the crevasse fill ridge in Clara's Woods was being created, similar processes of ice pressing and subglacial squeezing, and differential ablation and topographic inversion were occurring simultaneously elsewhere, thus creating the well-developed hummocky terrain and kettle holes surrounding the south portion of Stony Brook University. It is likely that this hummocky terrain is actually composed of other basal crevasse squeeze ridges blanketed by till, similar to the study ridge, as crevasse squeeze ridges often occur in networks (Benn and Evans, 1998) and disappear under the glacial till of end moraines (Stewart *et al.*, 1988).

Based on Hanson's (2004) conclusion that the Stony Brook area is the product of three ice-lobe advances and retreats, it is likely that pro-glacial folding and thrusting, subglacial squeezing, differential ablation, and topographic inversion occurred multiple times in the area, therefore redistributing sediments and erasing and reforming landforms. The well-developed landforms observed today are those that have been preserved, and are of importance since such landforms are only occasionally encountered.

Due to the geographic location of the Clara's Woods ridge and the surrounding terrain, it is proposed that the study ridge was formed during the first advance identified by Hanson, as this is the only advance of the three he identified, in which the ice sheet would have overridden the area where the ridge was produced.

Implications for Glacial Setting

The orientation of the ridge relative to the local north-south ice flow direction suggests the glacial crevasse was transverse to the ice margin at the time of ridge formation. As such, compressional stresses must have acted on the ice sheet in a north-south orientation, thus creating the east-west tensile stresses necessary to open the crevasse. The presence of such stresses would not have been constrained to the ice above the Clara's Woods area, but would have extended throughout the Stony Brook region. This implies that multiple crevasses may have formed, resulting in a network of crevasse-related landforms, which have yet to be identified.

The presence of such squeeze-related features in the Stony Brook area indicates that this section of the Laurentide Ice Sheet may have surged, as Sharp (1985) considered crevasse squeeze ridges to be particularly diagnostic of former ice surges (Benn and Evans, 1998). If this is true, such surging action may help to explain the origin of the three segments of the Stony Brook Moraine as identified by Hanson (2004).

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