Further Ground-Penetrating Radar Investigations into Hither Hills Glacial Tectonism

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Introduction

Continuing ground-penetrating radar (GPR) surveys at Hither Hills State Park, near Montauk Point, are being conducted to determine the origin of a remarkable pattern of hills in the area. A chain of 20 m-high, regularly-spaced hills organized in linear, ENE-WSW trends gives the park a very distinctive character. The resemblance of this area to features observed at the margins of present and past glaciers throughout the world leads us to surmise that its origin involves dynamic processes related to an advancing (and possibly overriding) glacier, either beneath it or beyond its margin. Our radar surveys have imaged shallow reflective layers following topography, suggestive of the folding of formerly flat-lying layers, as well as a strong, continuous deep reflector that can be traced throughout the study area. In addition, a detailed survey of a dendritic network of valleys in the park is postulated to represent a tunnel valley.

Background

Forms and Processes of Glacial Tectonism

The stresses imposed by the physical pushing, basal shearing, and gravitational loading of a glacier can have a significant impact upon the surrounding geological environment. There is a variety of ways in which positive topographic landforms can be created by imposition of these stresses. Subglacial shearing and loading, especially involving saturated, unconsolidated sediments beneath warm-based glaciers, can cause fluidization and pressure-driven flow of the basal material upwards into radial or margin-parallel crevasses, creating small diapiric ridges. For a cold-based glacier encroaching upon a similar environment, layers of basal material may "freeze onto" the base of the glacier, be partially incorporated, and be either dragged, thrusted, or transported englacially in the direction of glacial movement, to be deposited during the melting of the glacier.

Proglacially, unconsolidated materials may be pushed and/or folded by the advancing glacier into small mounds (Fig. 1a), creating a characteristically asymmetric profile with a steeper distal side (*Eybergen*, 1987). This process can take place as the culmination of a single glacial advance or seasonally as the glacier readvances each winter into recent sediments deposited during the summer ablation. In addition, in the presence of more consolidated sediments, a basal aquiclude and/or margin-sediment coupling, a décollement may form at depth, allowing the propagation of thrust faults and the uplifting and gliding of thrust blocks in a manner similar to the "bulldozer" model of fold-and-thrust orogenic tectonics (Fig. 1b; *e. g.*, *Croot*, 1987; *Boulton et al.*, 1999). Other glaciotectonic processes have been noted and some combination of these processes may be present, whether each style operates in different zones or in concert, at any one glacier (*e. g.*, *Boulton et al.,* 1999). The potential roles of pore fluids (serving as a lubricant as well as lowering the effective pressure of the glacial overburden) and permafrost (providing an effective décollement surface or increasing the coupling between the glacier and the underlying/proglacial sediments) in these processes have been intensely debated in the literature.

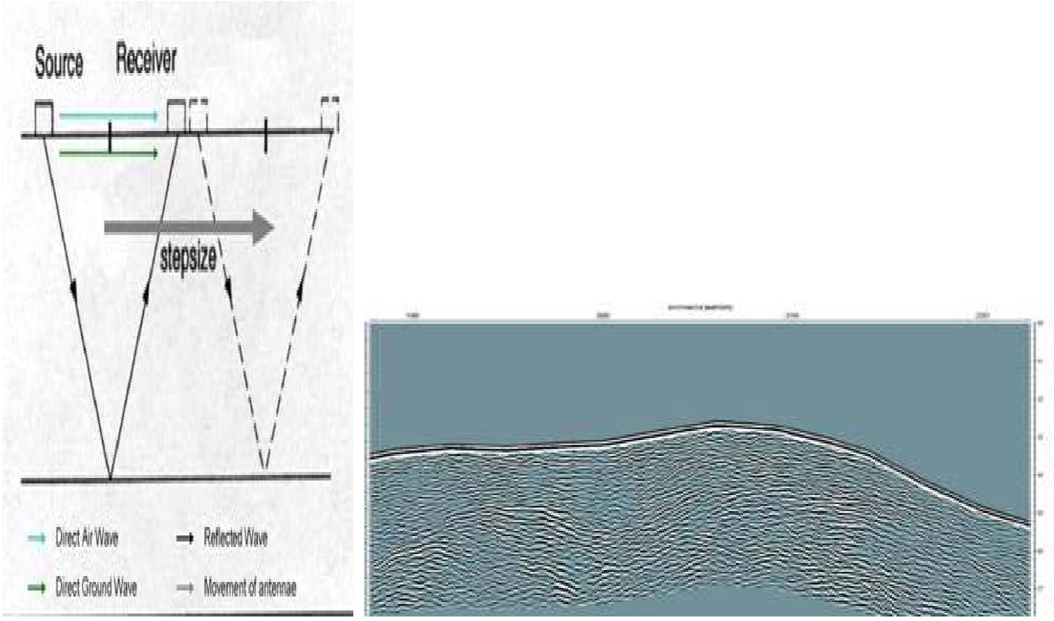


Fig. 1: Various models of proglacial glaciotectonic ridge formation. 1A (left): repeated episodes of pushing and folding against unconsolidated proglacial sediments; B (right): proglacial thrusting in a manner similar to orogenic foreland fold-and-thrust belts. The sequence of numbers in 1B suggests that thrusting begins with the ridge nearest the glacier and proceeds outward, while from 1A it is clear that the youngest push ridge is formed most distally. The internal structures also show differences: push ridges consist of discontinuous folded layers, while thrust ridges have tilted layers meeting at a detachment.

Each of these processes imposes a characteristic structure upon the existing sedimentary bedding (if any) of the deforming environment. For instance, the rafting of glacially-incorporated (but relatively undeformed) beds would juxtapose units of discontinuous bedding, whereas proglacial thrusting would produce tilted beds and a décollement at depth. It is our intent to determine the subsurface structure of and possible glaciotectonic processes once active in the Hither Hills region, use this information to characterize its origin, and, if possible, correlate this origin with other glaciotectonic features across Long Island in order to ascribe its formation to a particular glacial advance.

Did You Say "Other Glaciotectonic Features Across Long Island?"

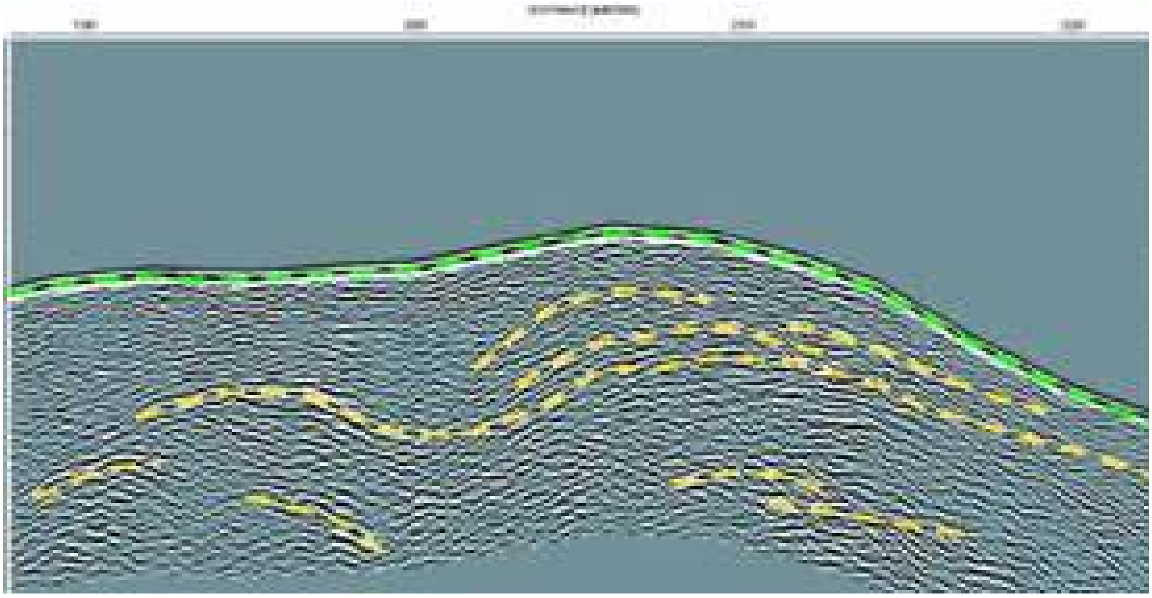


Fig. 2: Map of Long Island displaying the two principal moraines and the general location of the Hither Hills.

Both of the principal moraines of Long Island show good examples of glaciotectonic deformation created during their construction. As long as a century ago, locales in both the northern Harbor Hill and southern Ronkonkoma Moraines (Fig. 2) were recognized as displaying glaciotectonic features, and more recent studies have revealed further evidence for glacial deformation (*Merrill*, 1883; *Donner*, 1964; *Nieter et al.*, 1975). For instance, *Mills and Wells* (1974) and *Selvaggio and Richard* (1999) documented glacially folded and faulted features on the north shore coasts, and *Meyers et al.* (1988) mapped the presence of coherent glacially-thrust blocks in the Ronkonkoma Moraine, displaced several tens of meters above and hundreds of meters or more laterally from their source (Fig. 3). Although these features have undoubtedly been deformed glacially, the subsurface geometry of these folds and faults, and therefore the mechanisms of their emplacement, generally remain unclear, as does the nature of the environment - both physical and climatic - that led to their formation. This merits a subsurface investigation of a unique area which is also believed to have been deformed glacially.

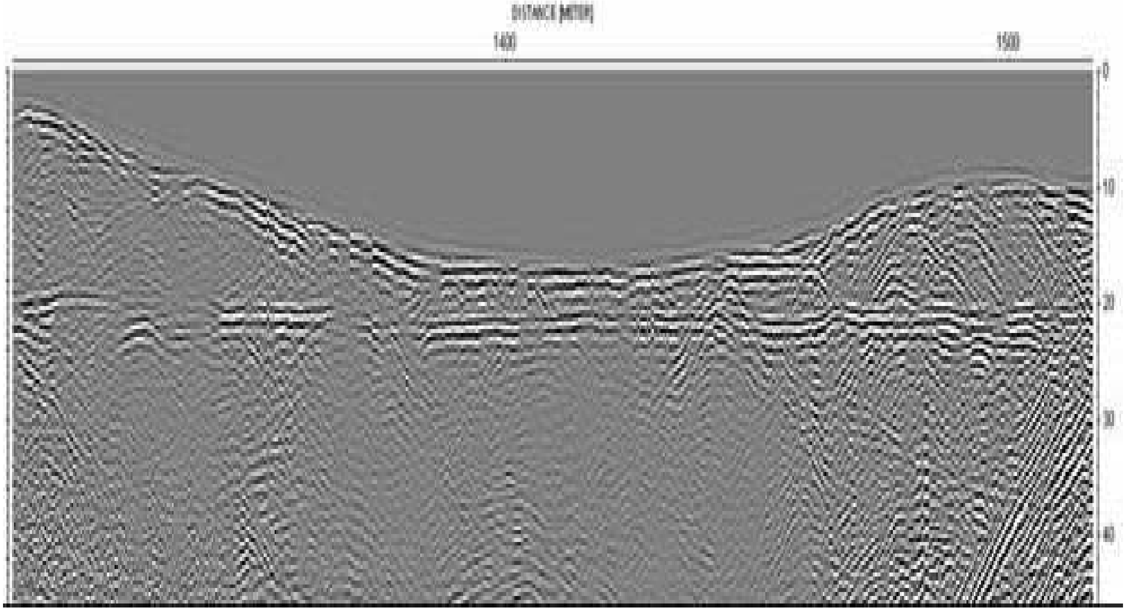


Fig. 3: Interpreted photomosaic of glacially-thrusted strata in Ranco Quarry, southern Suffolk County.

Procedure

Study Area

Hither Hills State Park is located about 15 km to the west of Montauk Point on the southern fork of eastern Long Island (Fig. 2). The location of the park on a portion of the Ronkonkoma Moraine, which is thought to represent a marginal position of the last Wisconsinan ice sheet, makes it a prime candidate for the formation of glaciotectonic features, as they are often concentrated near the margins of glaciers. The park features a long trend of regularly-spaced, NE-SW-trending hills, subparallel to each other but falling in groups of hills with slightly different geometrical orientations (Fig. 4A). They vary in height and spacing, but topographic relief from crest to trough is typically on the order of 10-15m and distance from crest to crest varies from 80-200m. Another unique feature is visible in the northern third of the park: a dendritic network of valleys cuts across the trend of these hills.

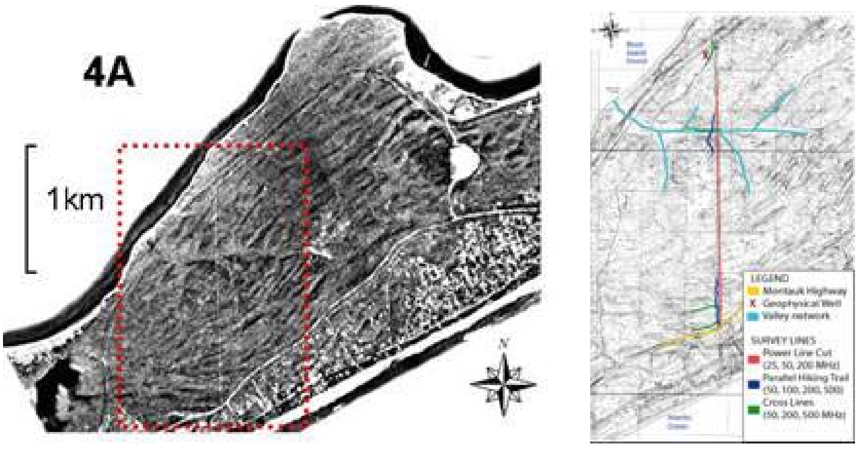


Fig. 4: Hither Hills State Park region. See Fig. 2 for location. A: Aerial photo of park. Clearly visible is the ENE to NE-trending chain of elongated subparallel hills. Their origin is the object of this study. Also visible is the N-trending vehicle trail used in the survey (Power Line Cut: PLC) and the dendritic valley network 3/4 of the way up the PLC. B: Enlarged topographic map of study area (highlighted in A) showing location of survey lines and other features. Both figures link to larger versions.

Several viable geologic models have been suggested for the formation of the hills. Sirkin (1983; 1995 p. 46) envisioned the features as recessional moraines deposited during the orderly retreat of the Wisconsinan ice, while *Fuller* (1914) attributed them to glacial meltwater erosion. Any of the glaciotectonic methods described above may also be proposed as an alternative. In our working model, the advance of an active glacier pushed or thrusted proglacial sediments into hills which mirror the shape of the margin at the time. The hills may represent a thrust complex related to a single advance (*e. g., Schluchter et al.*, 1999) or individual advance episodes related to seasonal or longer-scale margin fluctuations (*e. g.*, *Sharp*, 1984). These processes would involve the deformation of previously existing flat-lying beds of proglacial outwash and/or preglacial sediments.

Subperpendicular to the trend of these hills is major north-trending trail (more than 2 km long) intersecting Montauk Highway (Fig. 4A, B), which is the former site of a series of poles carrying power lines across the south fork. For this purpose a roughly 5 m-wide vehicle trail, here referred to as the Power Line Cut (PLC), across the hilled region was cleared by the Long Island Lighting Company for maintenance service. The presence of this path makes the area relatively accessible, and several hiking paths branching off of it are fairly well suited to radar surveys. The PLC also crosses the main "trunk" of the dendritic network of valleys at a fairly wide point, allowing a radar survey of this feature as well.

Basics of GPR

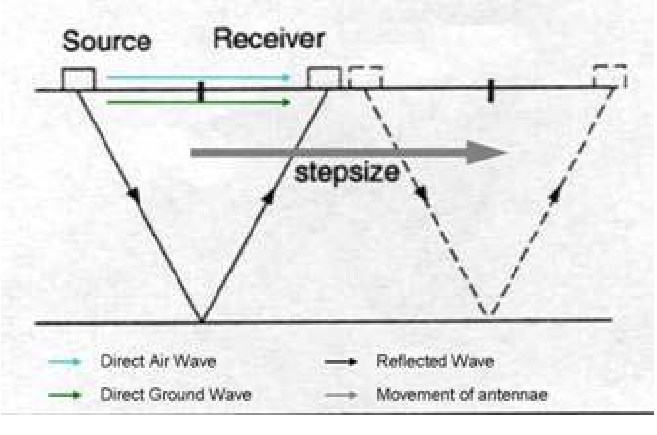
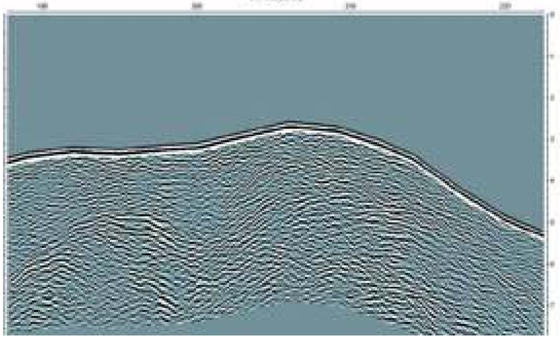


Fig. 5: Basics of GPR. An electromagnetic wave is transmitted into the subsurface (here represented by a single raypath), where it reflects off of a surface point or layer of differing electromagnetic properties. The reflected wave is recorded by a receiving antenna moved in tandem with the transmitter. As the system is moved stepwise across a survey line, a two-dimensional subsurface map is constructed. After van der Kruk et al.,*1999.*

Ground-penetrating radar (GPR) involves the emission, subsurface reflection, and recording of electromagnetic radiation. It is typically used for the lateral mapping of subsurface sediments which are characterized by differing electromagnetic properties. A transmitting antenna is moved along a prescribed line, emitting pulses which can reflect off of underlying objects and layers. These reflections are recorded by a receiving antenna, which for this survey is moved in tandem with the transmitter (Fig. 5). Hardware attached to the antennae is able to transfer this information to a laptop, where acquisition software displays the reflections as a series of "wiggles" in a two-dimensional display. This display, called a *radargram* (Figs. 6-8), represents an electromagnetic map of the subsurface: horizontal distance traveled in the course of the survey is plotted from left to right on the horizontal axis of the radargram, while the vertical axis represents the time it takes for the pulses to travel through the ground, reflect off of a subsurface reflector, and return to the receiver. After constraining the average velocity of the subsurface material (by consulting a reference table, measuring the time to an object at known depth, or interpreting the shapes of particular reflection patterns), the travel time can be approximately converted to depth (Fig. 5, 6; *van der Kruk et al.*, 1999).

Survey Methods

GPR surveys were initially conducted using 500 (high-resolution, shallow penetration), 200, and 100 MHz (lower-resolution, relatively deep penetration) antennae, mainly for about 300 m along a N-S hiking trail parallel to the PLC (Fig. 4B). The results of these surveys were quite encouraging, and in order to gain more information regarding these findings, the survey was expanded to include the PLC itself, using the 50 and 25 MHz (extremely low frequency and almost unparalleled penetration) antennae (Fig. 4B). This served a number of purposes: 1) a buried utility pipe beneath the PLC provides a strong reflector that could interfere with the radargrams obtained with the higher frequency antennae. The greater penetration and poorer resolution (*i. e.*, the diameter of the pipe is negligible compared to the long wavelength and thus poor resolution of the low-frequency antennae) allow us to avoid this complication; 2) it is hoped that at great depths more significant structural features, including perhaps a décollement surface, may be visible; 3) placing the previous high-frequency survey data into a larger context using the gross subsurface structure revealed by the low frequency antennae allows us to inter-pret each feature independently while relating it to the overall glaciotectonic model. To attain a measure of understanding of the three-dimensional behavior of these layers, cross lines perpendicular to the trend of the N-S surveys were run along E-W hiking trails, using the 200 and 50 MHz antennae (Fig. 4B).



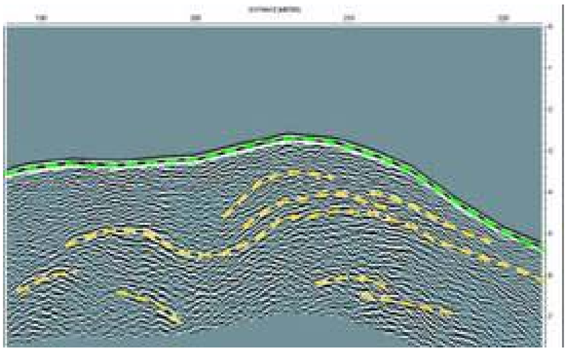


Fig. 6: Typical 500 MHz radargram of N-S trail parallel to PLC, here 185-225m. The horizontal axis represents distance traveled on the survey, while the vertical axis is time traveled through the subsurface, converted to depth. Left: radargram; Right: interpretation of data. Clearly visible are several shallow layers (yellow) following topography, suggestive of glacial folding. Vertical exaggeration about 2.50. Each figure links to a larger version.

In the area where the PLC crossed the "trunk" of the dendritic valley network, 50 and 200 MHz surveys were run along the PLC, revealing a prominent reflector which merited further attention. Therefore, further 200 and 500 MHz surveys were run along the north-south hiking trail 30 m to the west, while perpendicular surveys using the same frequencies were run along a portion of the E-W trending trunk. Further surveys near a geophysical and observational well of the SCWA (Fig. 4B) allowed us to calibrate the velocity of the subsurface against a known stratigraphic column.

Results

Initial results from the high-frequency surveys along the hiking trails revealed the presence of coherent reflectors which roughly followed the undulating trend of topography (Fig. 6). These layers could be traced across entire hills, and in some cases across several hills and valleys. These were interpreted to represent continuous beds which had subsequently been folded by an active glacial margin, whether in direct contact with the margin or as part of a proglacial foreland fold-and-thrust system. 200 MHz cross lines showed a similar trend: coherent reflective layers were imaged which were dipping consistently with the topography, albeit more gently in accord with the gentler topography perpendicular to the PLC trend (parallel to the strike of the hills). While processing the signal, it was possible to juxtapose the north-south and perpendicular lines and observe that in three dimensions some of the layers dip as a planar surface to the north.

The lower frequency surveys (Fig. 7) showed that these reflectors continue to greater (more than 10 m) depths. Also indicated was the presence of a bright reflective zone generally at about 20-30 m depth. When topography was accounted for during processing, this zone appeared reasonably flat relative to sea level and was able to be followed clearly for 100 or more meters in some places. However, it occasionally seemed to "die out" for several tens of meters, and over the course of the PLC dips apparently to the north. It has not yet been possible to characterize its behavior in three dimensions, due to a dearth of high-quality low-frequency cross lines.

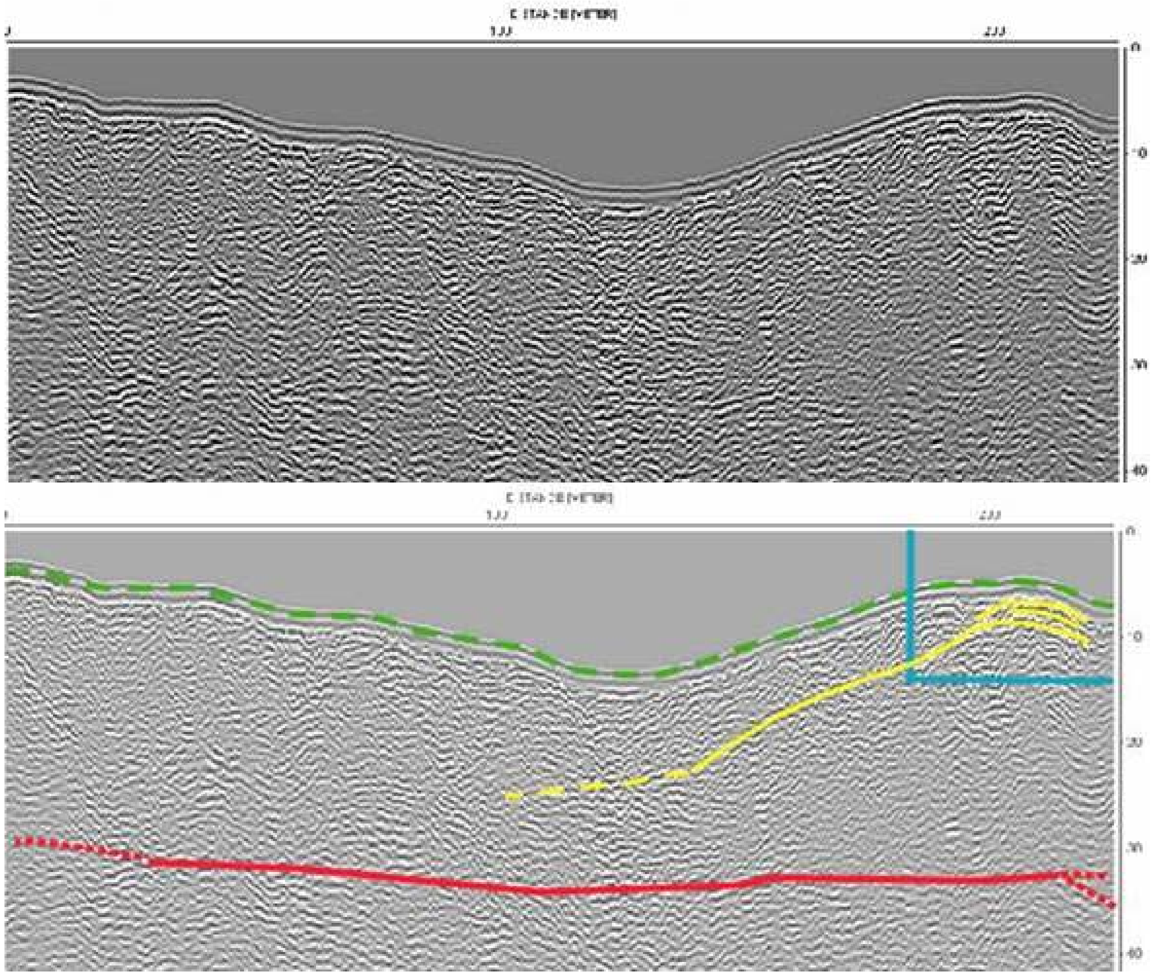


Fig. 7: 50 MHz radargram of hiking trail parallel to PLC from 0-225 m (area of Fig. 6 highlighted by blue box). Top: radargram; Bottom: interpretation. The folded layers from Fig. 6 are shown continuing to greater depth. Also prominent is the deep reflective zone (red), here lying flat at almost exactly 30 m depth. Almost all of the "folded" reflectors in the region terminate above this layer, suggesting the basal detachment associated with glaciotectonism lies at or above this level. Vertical exaggeration about 2.25:1. Both figures link to larger versions.

In the area of the trunk of the dendritic valley network, the low topography brings the deep reflective zone to an abnormally shallow level (within a few meters of the surface: Fig. 8). While the zone appeared as a coherent stratigraphic layer to the 50 MHz antennae (resolution about 45cm), it was rep-resented in the 200 MHz radargram as an unexpected series of single point reflectors: this placed bounds on the size of particles constituting the zone (cobbles to smallest boulders), and ruled out the possibility of this reflector representing a water table. The folded layers of the hills also seemed to lie above this zone throughout the survey area, meaning that a structural detachment likely lies at or above this layer.

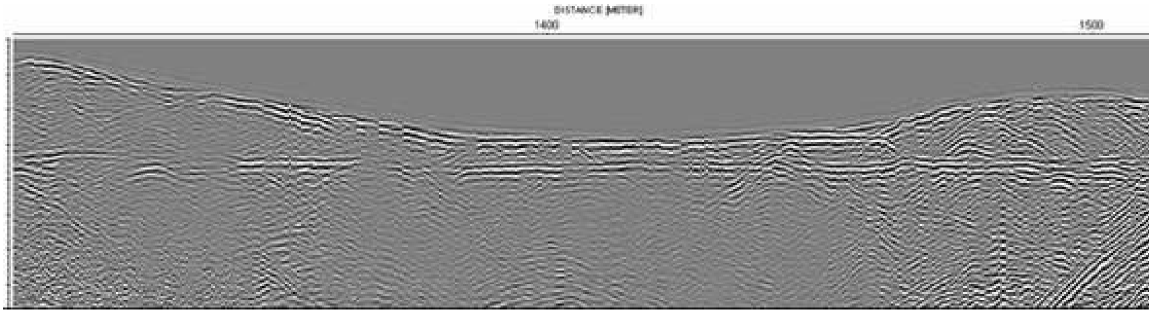


Fig. 8: 50 MHz radargram of the PLC along the "trunk" of the dendritic valley network. The deep reflective zone is brought to its shallowest point by extensive erosion. Higher frequency surveys (not shown here) show that rather than a coherent layer, as it appears here, the reflective zone is created by a series of closely-spaced cobble-sized reflectors. This is suggestive of a till. The valley itself is thought to represent the main channel of a tunnel valley. Vertical exaggeration about 2.75:1.

As for the nature of the valley network itself, its dendritic pattern plainly indicates erosion via fluvial processes of some sort. It is clearly younger than some of the glacial deformation, as it prominently cross-cuts several hills (Fig. 4). However, in some places the water seems to have followed the topography of the hills before finding an outlet. Given the west orientation of the dendritic pattern (opposite that expected for simple outwash streams), the sheer scale of the feature (lateral extent as well as amount of erosion), and its ambiguous relation to the topography, we surmise that it represents the result of headward erosion due to highly-pressurized subglacial water flow, *i. e.* a tunnel valley.

In many places, both the folded layers in the hills and the deep reflector beneath were discon-tinuous, which could represent a temporary cessation of tectonism. This observation, coupled with the sedimentologic heterogeneity and subtle variations in the orientation of small groups of hills, suggests that the hills were caused by fluctuation of the glacial margin, whether on the scale of seasons or decades or more, in the manner described by *Sharp* (1984) at a current glacier in Iceland: as the glacier recedes, it deposits sediments in a proglacial pool or lake; the following winter it advances and pushes or thrusts the unconsolidated, often saturated sediment, forming individual hills while undergoing a net retreat at a yearly time scale. The larger scale of the Hither Hills, however, suggests that each push event was of longer duration than a single season. Differences at the pertinent time scale in the marginal, englacial, and upglacier basal sediment supply could easily provide the heterogeneous nature of the individual hills.

Conclusions/Future Work

Hither Hills State Park appears to display several features consistent with formation by glacio-tectonic processes. At the large scale, a suspicious reflective zone at about 20-30 m depth could represent a zone of detachment or an underlying till, while shallower features such as dipping reflectors that are clearly mimicking the undulating topography represent small-scale structures that interact in a complex manner with each other and with the underlying reflective zone. A tunnel valley is postulated to have been carved beneath the glacier, perhaps syntectonically, creating a west-trending network of valleys.

Additional work in the area will involve collection of more high-frequency data in select locations of the PLC where deformation is clearly taking place at shallow to intermediate depth, as already determined by the low-frequency antennae. While the terrain restricts us to relatively few areas suitable to survey lines (particularly cross lines), it is necessary to constrain further the exact nature of these structures in three dimensions. This information can allow us to determine how well they correlate with the topography, giving perhaps a gauge as to how old these features are and possibly assign them to a specific glacial advance. In addition, the shallowing of the prominent reflective zone near the tunnel valley could present a potential target for direct geologic sampling by augering. Finally, comparing the distribution of these landforms with regional climate records might show whether a sustained advance long enough to have constructed the hills was possible.

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