LiDAR-based Glacial Geology of the Halifax Metropolitan Area

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Introduction

Spectacular images of glacial geomorphology features, especially drumlins, are evident in the ‘bare-earth’ model of a LiDAR survey carried out in the Halifax metropolitan area. Subtle variations in drumlin orientations and shape are clearly defined on the LiDAR imagery, allowing for identification of previously unmapped features that can be used to interpret glacial history.

The surficial geology of the greater Halifax area was last mapped at a scale of 1:100 000 by Stea and Fowler (1979, 1981), then compiled and updated by Stea *et al.* (1992), with some portions of the western edge covered by Finck *et al.* (1992), mapping at 1:50 000 and compiled to 1:250 000. The objectives of these mapping programs were primarily driven by mineral exploration, and included investigations into the area’s glacial history to better understand the provenance of the glacial deposits. The mapping was based on aerial photography (1:10 000), Canadian Soil Information System soil data, and field observations (striation and till fabric measurements, pebble lithologies). The small scale of the maps has limitations, especially as it is too coarse for land-use planning and hydrogeologic modelling applications. The LiDAR survey of the area (Fig. 1), collected by the Halifax Regional Municipality in collaboration with the Geological Survey of Canada (Atlantic), provides an opportunity to dramatically improve the detail of surficial mapping. The ‘bare earth’ hillshade model of the data gridded to 2 m also allows for interpretation of glacial history that would otherwise be obscured by vegetation.

This paper outlines some preliminary interpretations of features on the LiDAR images and resulting implications for glacial history of the area. This work is significant because large quantities of distally derived sediment with varying geochemical and geotechnical properties were transported into the area during different glacial phases.

Bedrock and Physiographic Setting

The bedrock of the area includes the Cambrian to Ordovician Meguma Supergroup (Goldenville and Halifax groups), which is intruded by the Devonian-Carboniferous South Mountain and Musquodoboit batholiths and the Kinsac Pluton (White *et al.,* 2008; Creaser, 1997) (Fig. 1). These rocks have been eroded since the Jurassic to form a paleo-surface dipping gently southeastward (Fader and Miller, 2008), and are part of the Atlantic Uplands (Bostock, 1970). A series of northwest-striking joints, faults, veins and dykes over the generally west-striking Meguma Group controls the orientation of rivers crossing this surface (Fader and Miller, 2008), with a mainly southwestward trend over the South Mountain Batholith and a south-to-southeastward trend over the Musquodoboit Batholith and Kinsac Pluton (Burt and Fisher, 2006). A trough cuts as much as 100 m below the upland paleo-surface and connects Shubenacadie Grand Lake with Bedford Basin.

In the study area, the Goldenville Group consists of the Taylor Head Formation, a predominantly thickly bedded metasandstone, interbedded with cleaved metasiltstone and slate (White *et al.,* 2008). This is stratigraphically overlain by the Halifax Group’s Beaverbank, Cunard and Bluestone formations, composed of thinly bedded to laminated metasiltstone and slate with lesser amounts of metasandstone (White *et al.,* 2008). The Beaverbank Formation is interpreted to represent the transition between metasandstones of the Taylor Head Formation and slates of the rest of the Halifax Group (White *et al.,* 2008). The batholiths and pluton consist of coarse-grained to megacrystic granodiorite to monzogranite and leucomonzogranite (White *et al.,* 2008).

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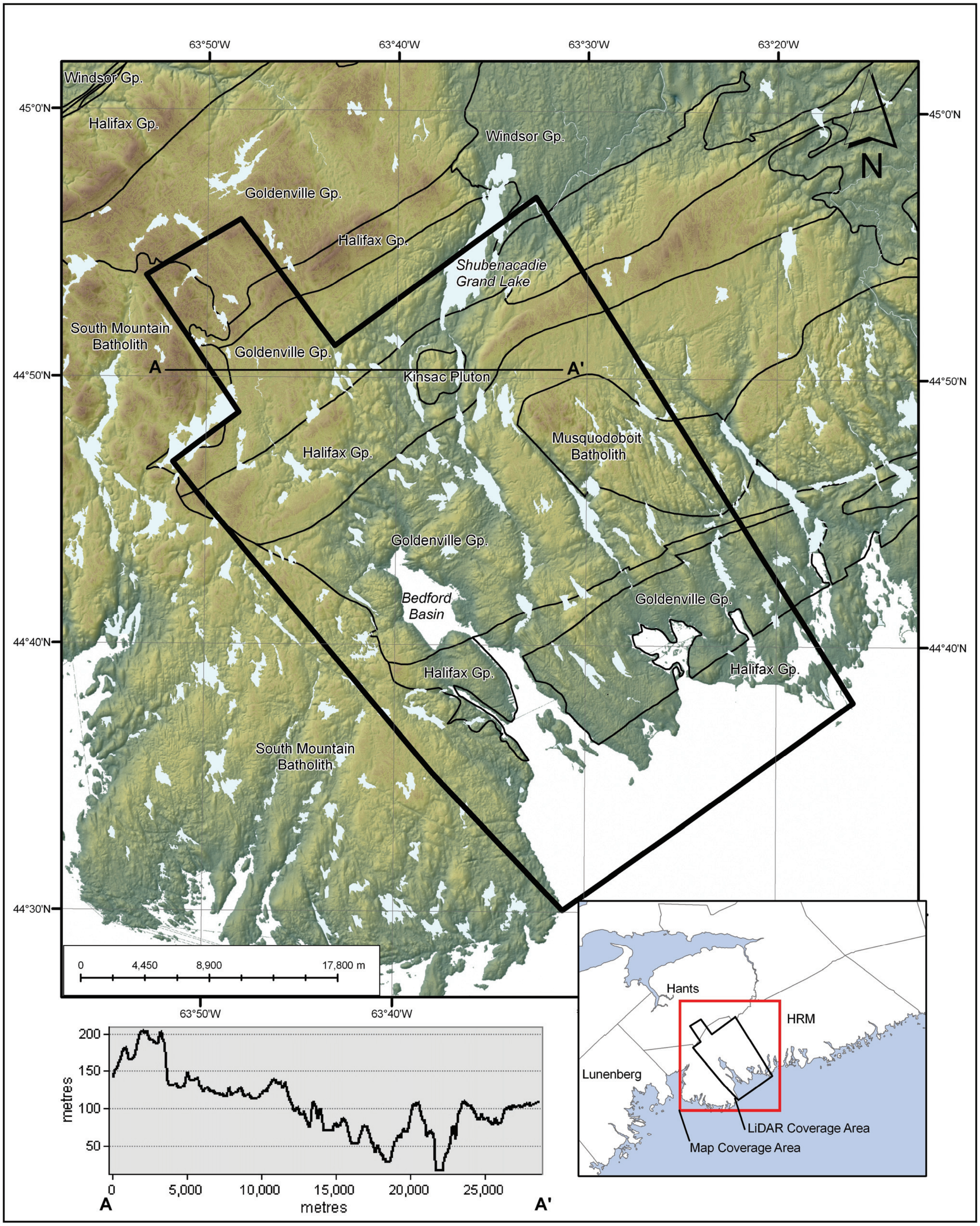

Figure 1. Location of study and LiDAR survey area. Bedrock geology modified from Keppie (2000). Note general structurally controlled trend of physiographic features toward the southeast. Topographic profile A-A[1] is perpendicular to a trough cutting the paleo-surface between Shubenacadie Grand Land and Bedford Basin.

Quaternary History

Although some pre-Wisconsinan events are recorded elsewhere in the province, the oldest glacial event to be recorded by a till deposit in the Halifax area is marked by the Hartlen Till (Stea, 2004). This was deposited by east to southeastward flow from a regional ice sheet that may have crossed the province from New Brunswick (Caledonia Phase; Stea, 2004).

At maximum glacial conditions, ice flowed from the Magdalen Shelf to the continental shelf edge, flowing from an ice divide oriented oblique to the length of Nova Scotia, from the Strait of Canso past Prince Edward Island (Shaw *et al.,* 2006, their Fig. 8) or from an ice dome ("Escuminac Dome") over the Magdalen Shelf (Stea *et al.,* 2001). During this phase, ice streams crossed the province forming drumlin fields and depositing Lawrencetown Till in the Halifax area (Grant, 1989). The glacial flow path that deposited Lawrencetown Till at the West Lawrencetown section was defined precisely by Stea and Pe-Piper (1999) from erratics in the till. Some of the igneous erratics can be correlated to a specific pluton in the eastern Cobequid Highlands near Truro, narrowing a 'provenance envelope' that indicates the ice stream transported material southwards from the Magdalen Shelf before being deposited at Lawrencetown (Stea and Pe-Piper, 1999). The terminus of these ice streams was marine based, either at the continental shelf edge or an ungrounded floating ice shelf. On the continental shelf, flow was probably directed via the Emerald Basin (Piper, 2000, his Fig. 1; Fader and Miller, 2008, their Fig. 141).

Following this maximal phase, an ice divide formed oriented parallel to the length of Nova Scotia along the centre of the province ("Scotian Divide" of Stea *et al.,* 2001), or parallel to the present-day coastline (Shaw *et al.,* 2006), as a result of drawdown into the Fundy Ice Stream. This phase resulted in deposits of the locally derived, clast-dominant Beaver River Till (Stea, 2004). During this phase ice was retreating across the shelf edge and formed a series of recessional moraines known as the Sambro, Southshore, Pennant Point and Halifax moraines (Fader and Miller, 2008). These moraines, among others, are segments of the Scotian Shelf End Moraine Complex, located 30-40 km offshore at depths of 125-175 m (King, 1996). The youngest moraine (i.e. closest to coast) offshore from Halifax Harbour is the Halifax Moraine, which has been assigned an age of 15.0 ka based on correlations with flanking moraines (Eastern Shore and Country Harbour) and from radiocarbon samples from till tongues proximal to those moraines (King, 1996). These moraines likely formed at the floating margin of a low-gradient ice sheet, and the till tongues are deposited proglacially to that margin by a series of gravity flow aprons interdigitated with fossiliferous glaciomarine sediment, in this case Emerald Silt (King, 1996).

Properties of Different Tills

Lawrencetown and Beaver River tills, as discussed above, have very different geotechnical and geochemical properties. Lawrencetown Till is found within drumlins in the study area. It is not found as a till blanket, as reported by earlier workers (Lewis *et al.,* 1998), but in some cases forms low-drumlinized terrain. It is a reddish, muddy till derived from Triassic bedrock in the Magdalen Shelf and Cobequid Highlands to the north (Stea and Pe-Piper, 1999). At many sections this till is found to overlie an older Hartlen Till, a grey, silty till with locally derived clasts (Stea and Finck, 2001). Beaver River Till is a sandy till with locally derived clasts eroded from underlying and up-ice bedrock (Stea and Finck, 2001). Lawrencetown Till has a higher effective cohesion and tends to retain moisture compared to Beaver River Till (Lewis *et al.,* 1998).

Ice-stream Features

Ice streams, areas of faster-flowing ice bounded by slower ice, are significant because they transport large quantities of distally derived sediment that has very different geochemical and geotechnical properties than the local material (Stokes and Clark, 1999). Where ice streams have been observed in modern environments they typically terminate in water, allowing for a rapid flux of ice and keeping ice velocities high, on the order of 300 m/yr (Stokes and Clark, 1999).

Some revealing features of ice streams in the Halifax area are visible on the LiDAR images that are otherwise obscured by vegetation. The Mount Uniacke area has the most elongate landforms of the LiDAR survey area (Fig. 2). They trend southeastward and are ~1 km long and ~200 m wide, with a length to width ratio of ~5. Marshall (1997) determined the average length to width ratio of drumlins in the Halifax area from airphotos to be 2.9. This average elongation ratio is low compared to other ice stream locations, which have ratios over 10 in fast flow areas (Briner, 2007; Stokes and Clark, 1999, 2002), and lower than the 7.2 reported for the ‘classic’ spindle forms near Livingstone Lake (Marshall, 1997).

The edge of the zone of streamlined landforms in the Mount Uniacke area is coincident with the contact between the South Mountain Batholith and Meguma Supergroup, with the streamlined features occurring on the latter. The edges of ice streams are typically marked by an abrupt margin or a lateral shear moraine (Stokes and Clark, 1999). On the LiDAR image of the area, the edge of the zone of streamlined landforms has long, low, elongate features, possibly a shear moraine. Finck *et al.* (1992), however, note that the area over the South Mountain Batholith is glacially scoured, with striae parallel to the streamlined features, but this erosion could be from other glacial events.

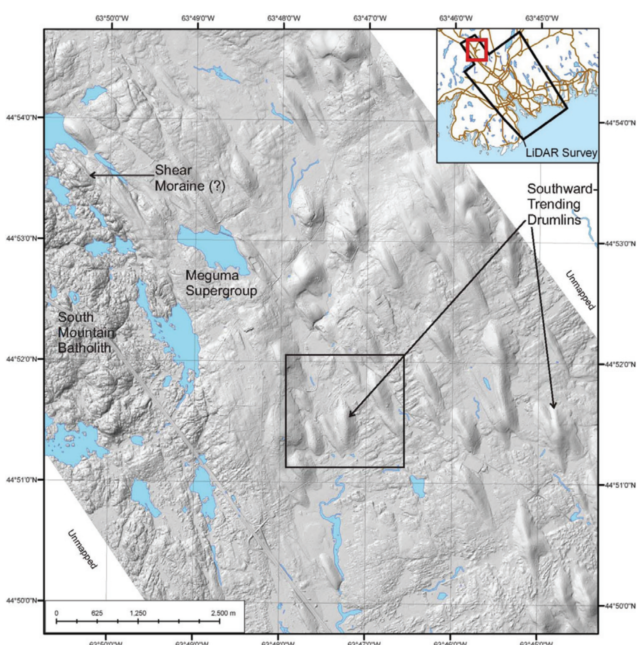

Figure 2. Bare-earth hillshade model of Mt. Uniake area. The western portion of this image is underlain by South Mountain Batholith granitic rocks that exhibit no glacial landforms, whereas east of that the area is underlain by Meguma Supergroup metasediments and there are numerous elongate drumlins. General trend of drumlins is toward the southeast, but a few are oriented toward the south. Box indicates location of Figure 4.

Ice-flow Phases

Two flow directions are evident in the Mount Uniacke area (Fig. 2), and also farther east in the Sackville-Kinsac area (Fig. 3), but the age relationships of these two phases are unclear from the LiDAR images alone, as there are no clear crosscutting relationships (Fig. 4). To determine the temporal relationship of these two flow directions the regional flow pattern is examined below, followed by a discussion of stratrigraphy from coastal sections (based on previous published work).

Glacial ice-flow lines can be interpreted based on drumlin orientations plotted from the LiDAR hillshade model and a regional pattern of ice flow becomes evident (Fig. 5). There are two ice-flow directions that influence the area: the ‘Mount

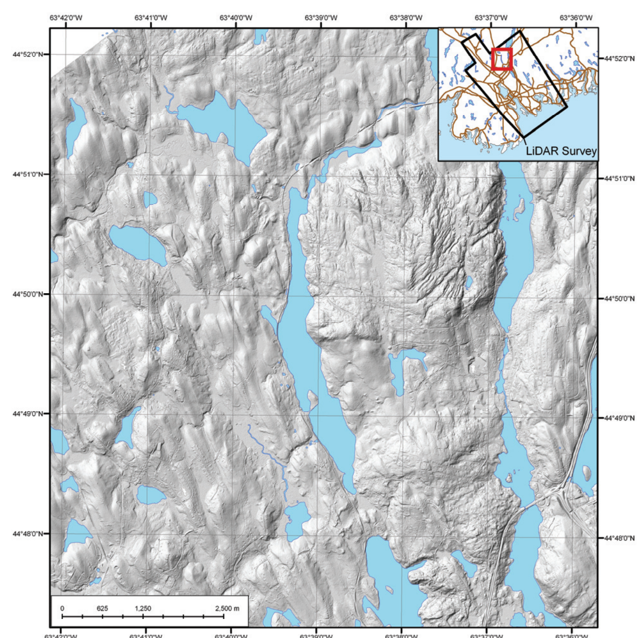

Figure 3. Bare-earth hillshade model of North Sackville-Kinsac area. Southward-trending drumlins appear to merge with the southeastward trend noted in Figure 2. Note the absence of glacial features on Kinsac Pluton, similar to on the South Mountain Batholith (Fig. 2).

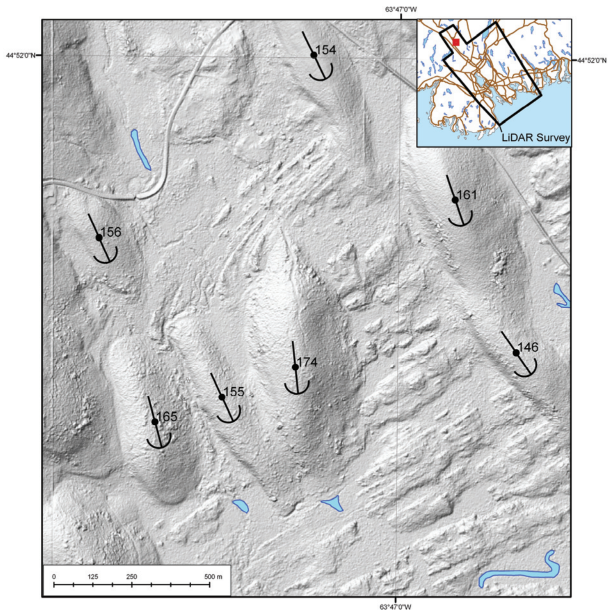

Figure 4. Close-up view of bare-earth hillshade model of southeastward- and southward-trending drumlins with no evident temporal relationship. Location of close-up shown on Figure 2.

Uniacke' flow toward the southeast, and a 'Kinsac' flow toward the south (Fig. 5). The two flows converge in an area near the '1' marked on Figure 5, north of Sackville. It appears as though the 'Kinsac' flow generally follows the valley between Shubenacadie Grand Lake and Bedford Basin, initially flowing toward the south, then flowing toward the southeast. The two flows are deflected, the southeast-trending 'Mount Uniacke' flow is deflected southward, and the southward-trending 'Kinsac' flow is directed toward the southeast. There is also some convergence of flow in the area marked by a '2' in Figure 5, but there is less deflection, likely because the flow directions are similar. The area marked '3' on Figure 5 has hummocky moraine, a typical feature at the edge of ice streams (Patterson, 1998), or possibly related to expanding flow after a zone of convergence. These interpretations suggest the two flow phases were in operation at the same time, and the fact that the 'Kinsac' flow was deflected by topography suggests this occurred when the ice sheet was thinning (i.e. during deglaciation).

Stratigraphy and till fabrics at the West Lawrencetown section reveal that there was an initial southeastward flow (depositing the Hartlen Till), followed by southerly flow (depositing the Lawrencetown Till), which was followed by southeast flow (forming the upper 'hybrid' till) (Stea and Pe-Piper, 1999). Initial interpretations of the Lawrencetown section and its relationship to landform morphology - based on topographic maps - suggested that the drumlin was originally formed by the southeastward flow that deposited the Hartlen Till, and was then modified by the southward flow that deposited the Lawrencetown Till (Stea and Brown, 1989). It is clear from the LiDAR image, however, that the latest drumlin-forming ice-flow direction (at this site) was toward the southeast (Note '4' on Fig. 5, Fig. 6). A possible interpretation is that the last southeastward flow direction that formed the hybrid till sculpted the drumlin form. The southward-oriented till may be better preserved at this site because it is on the lee side of a bedrock ridge that runs roughly perpendicular to the drumlin's long-axis about 150 m from the section (Fig. 6).

At this section there is a deposit of Lawrencetown Till that was clearly formed by southward flow, based on till fabrics and erratics that were derived from outcrops to the north (Stea and Pe-Piper, 1999). This southward flow may have crossed the region, including the Chebucto Peninsula where more southward-oriented drumlins are located (Stea *et al.,* 1992), flowing into the LaHave Basin. Sometime afterward this southward flow direction was deflected toward the southeast, either because of deflection by another southeast flow ('Mount Uniacke'), or because of topographic control. Topographic control likely became a bigger factor as the ice sheet thinned, suggesting that the change in flow direction happened during deglaciation.

Why So Fresh?

Drumlins on the LiDAR image appear as though the ice just left; their surface morphology is apparently unaltered by following ice-flow phases. The ice-flow phase that formed the drumlins, however, is supposed to have been followed by the Scotian Phase, which formed the locally derived Beaver River Till. How could a till-forming (i.e. eroding bedrock) ice-flow phase not erode or modify drumlins?

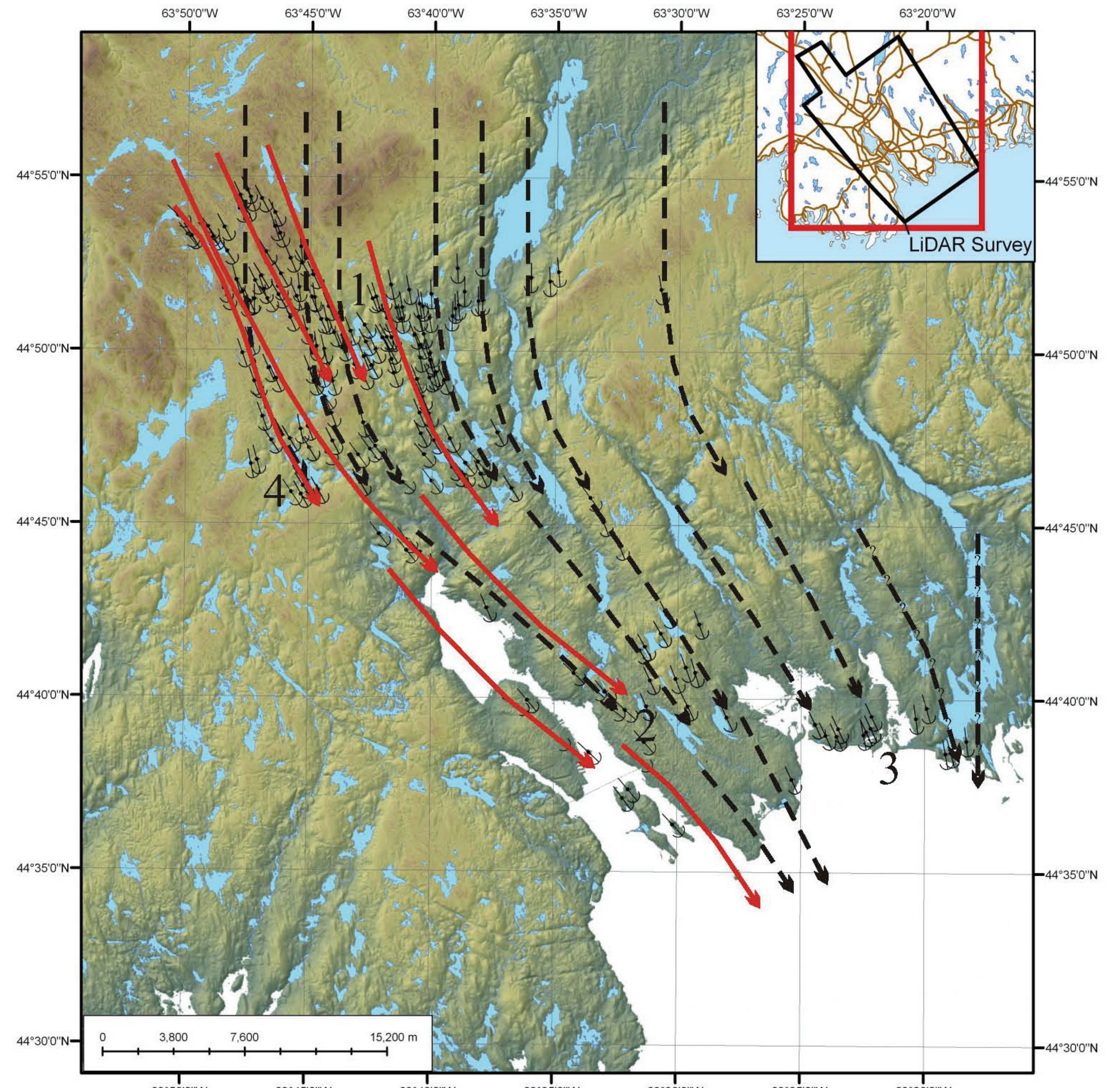

Figure 5. Provincial-scale DEM with drumlins and flow lines interpreted based on orientation of drumlins. 1- Area of converging southward ('Kinsac') flow and southeastward ('Mt. Uniake') flow. 2- Hummocky topography on outer edge of converging area. 3- Converging flow in Dartmouth area. 4- Lawrencetown area, where till formed by initial southward flow is reported in section, overlain by southeastward-trending till, parallel to surface morphology of drumlin.

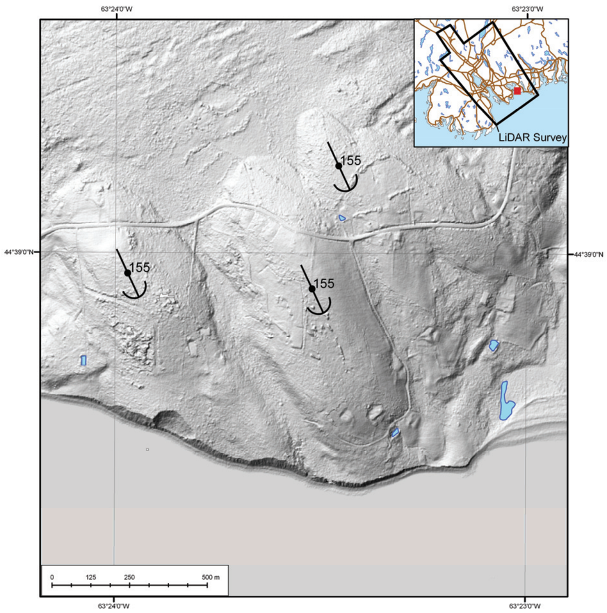

Figure 6. Close-up view of bare-earth hillshade model of drumlin at West Lawrencetown. Note 'fresh' trend of drumlin is toward the southeast. Previous interpretation of the palimpsest origin of the drumlins was based on less accurate topographic maps (cf. Stea and Brown, 1989). Thick southward flow derived till at the section may be due to preservation in lee of a bedrock ridge.

One possible scenario to explain the freshness of the drumlins is that much of the Beaver River Till may have formed prior to, or during the ice-streaming phase that formed the drumlins and that ice streaming persisted until later in deglaciation. If there was an early Beaver River Till it would have been eroded during the ice-streaming phase, explaining why this till is not observed in sections of drumlins beneath Lawrencetown Till. This scenario is plausible in many areas where there is little to no Beaver River Till overlying drumlins; there are, however, localities where thick Beaver River Till drapes the surface of drumlins (Fig. 7).

A more likely scenario is that the ice-flow phase that formed the Beaver River Till was parallel to the drumlin-forming phase. This is consistent with the till fabric at Lawrencetown (where the 'hybrid' till fabric is parallel to the axis of the drumlin). This does, however, suggest that the Beaver River Till was formed by the final stage of ice streaming, which is not consistent with previous interpretations about the depositional environment of this till, nor with the short transport distances reported for material in the till (Stea and Finck, 2001). The author plans to investigate this issue in the field season to come.

Summary

A LiDAR bare-earth hillshade model reveals spectacular images of the form and orientation of drumlins in the Halifax metropolitan area. The flow path of ice streams in the area can be determined from the orientation of drumlins that were otherwise obscured by vegetation. Initially there was a southward ice-flow phase that was later modified by a southeastward flow direction. These two flow directions are confirmed by till fabrics at the West Lawrencetown section. The 'un-eroded' appearance of the drumlins is remarkable, especially considering a later event is thought to have formed the Beaver River Till.

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Figure 7. Photograph of Lawrencetown Till overlain by Beaver River Till excavated during construction of the MicMac Parclo overpasses in the early 1990s in Dartmouth to replace the former MicMac Rotary. Photograph courtesy of R. Stea.

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