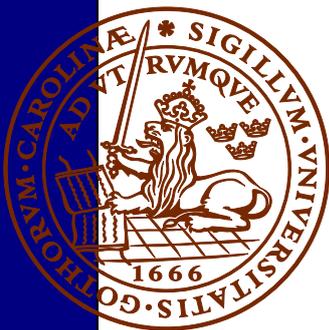


LiDAR mapping of presumed rock-cored drumlins in the Lake Åsnen area, Småland, South Sweden

Patrik Zaman

**Dissertation in Geology at Lund University,
Bachelor's thesis, no 458
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**Department of Geology
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2015**

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Cover Picture: Outcrop of bedrock on a drumlin in the area of Vemboö. Foto: Patrik Zaman.

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Abstract: The landform group called drumlins has since long been enigmatic; this study aims to shed some light on them. By mapping their extent in two areas around Lake Åsnen, Småland, southern Sweden, their extent and properties have been mapped with a level of detail that would have been next to impossible just a few years ago. The method used in this study utilized LiDAR derived high resolution hillshade models to map out the drumlins extent and investigate whether any outcrops of bedrock could be identified inside their rim. The mapped data's accuracy was then verified through a field survey. In total 201 drumlins were checked, 114 in the Vemboö area and 87 in the Torne area. The result showed that for the Vemboö area, 92.1%, and for the Torne area, 75.9%, of the drumlins were found to have a hard-core of bedrock. This indicates that it's probable that the drumlins where no bedrock could be identified also most likely has one, but situated at some depth superimposed by till and other sediments. The method of mapping bedrock outcrops through hill shade models also proved accurate in more than 95% of the cases; this shows that this method is so reliable that it might be recommended for use over larger areas without the type of extensive field verification carried out in this study.

Keywords: Drumlins, LiDAR, DEM, Digital Elevation Model, Rock-core, Bedrock-core, Streamlined terrain, Småland, Lake Åsnen.

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Subject: Quaternary Geology

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LiDAR kartläggning av misstänkta bergskärnedrumlinor runt sjön Åsnen, Småland, södra Sverige

Patrik Zaman

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Sammanfattning: Landskapsformen drumlin har länge diskuterats inom akademien och den här studien syftar till att sprida lite ljus över dem. Genom att kartlägga två drumlinområden runt sjön Åsnen i Småland, södra Sverige har deras utsträckning kartlagts med en precision som länge ansetts omöjligt. Detta gjordes genom att använda hög upplösta hillshade modeller framtagna från LiDAR data för att efter att ha analyserat deras utsträckning identifiera utsickande bergshällor som kan utgöra dess bergskärna. Säkerheten hos modellen undersöktes sedan genom en fältstudie. Totalt undersöktes 201 drumlinor, 114 runt Vemboö och 87 runt Torne. Resultatet visade att för Vemboö hade 92,1% alla drumlinor en bergskärna och för Torne 75,9%. Resultatet indikerar att det är troligt att drumlinerna som saknar identifierad bergskärna troligtvis har en som är övertäckt av sediment eller morän. Metoden för att identifiera bergskärnorna i modellen visade sig även ha en säkerhet på mer än 95%. Vilket är tillräckligt bra för att kunna rekommendera att metoden används på ett större område utan den behov av den stora fältstudie som skedde i anslutning till den här studien.

Nyckelord: Drumlinor, LiDAR, DEM, Digital höjdmödel, Digital Elevation Model, Bergskärna, Bergskärnedrumlin, Strömlinjeformad terräng, Småland, Åsnen.

Handledare: Per Möller

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1 Introduction

1.1 Aim of the study

This project aims to construct Digital Elevation Models (DEM's) derived from LiDAR scanned data over two drumlin swarms in southern Småland and on these height models map outcrops of bedrock in connection to identified drumlins. By conducting a field survey of the mapped area and checking each drumlin for outcrops of bedrock, the accuracy of the interpretation can be assessed. The results are used to conclude which drumlin type is dominant in the area, rock-cored versus non rock-cored, and by this contribute to the discussion of how drumlins of various types are formed.

1.2 Geological setting

This study was carried out in the area of Lake Åsnen, the second largest lake in Småland, South Sweden (Fig. 1). The region around Lake Åsnen is located above the highest shoreline on the south Småland pe-

neplain and the landscape predominantly consisting of shallow till and outcrops of bedrock. The bedrock is mainly made up of granite and intrusive acid and basic metavolcanic rocks from the Hallandian orogeny surrounded by the Svecokarelian orogeny (SGU). The lake regions major landforms consist of drumlin swarms, eskers and to the south of these a wide belt of hummocky and ribbed moraine (Fig. 1) (Möller & Dowling 2015). The drumlins in the area come in two types (Dowling et al. 2015): as (i) rock-cored drumlins and (ii) as sediment-cored drumlins or larger patches of sorted sediment with a streamlined top surface and with a till carapace (Möller & Murray 2015). Rock-cored drumlins are common within and around Lake Åsnen, having oval plan forms with blunt stoss ends and tapering off tails in the former ice-flow direction (Fig. 1), i.e. north to south, and with mean height/width of 6.3 and 320 meters, respectively (Möller & Dowling 2015).

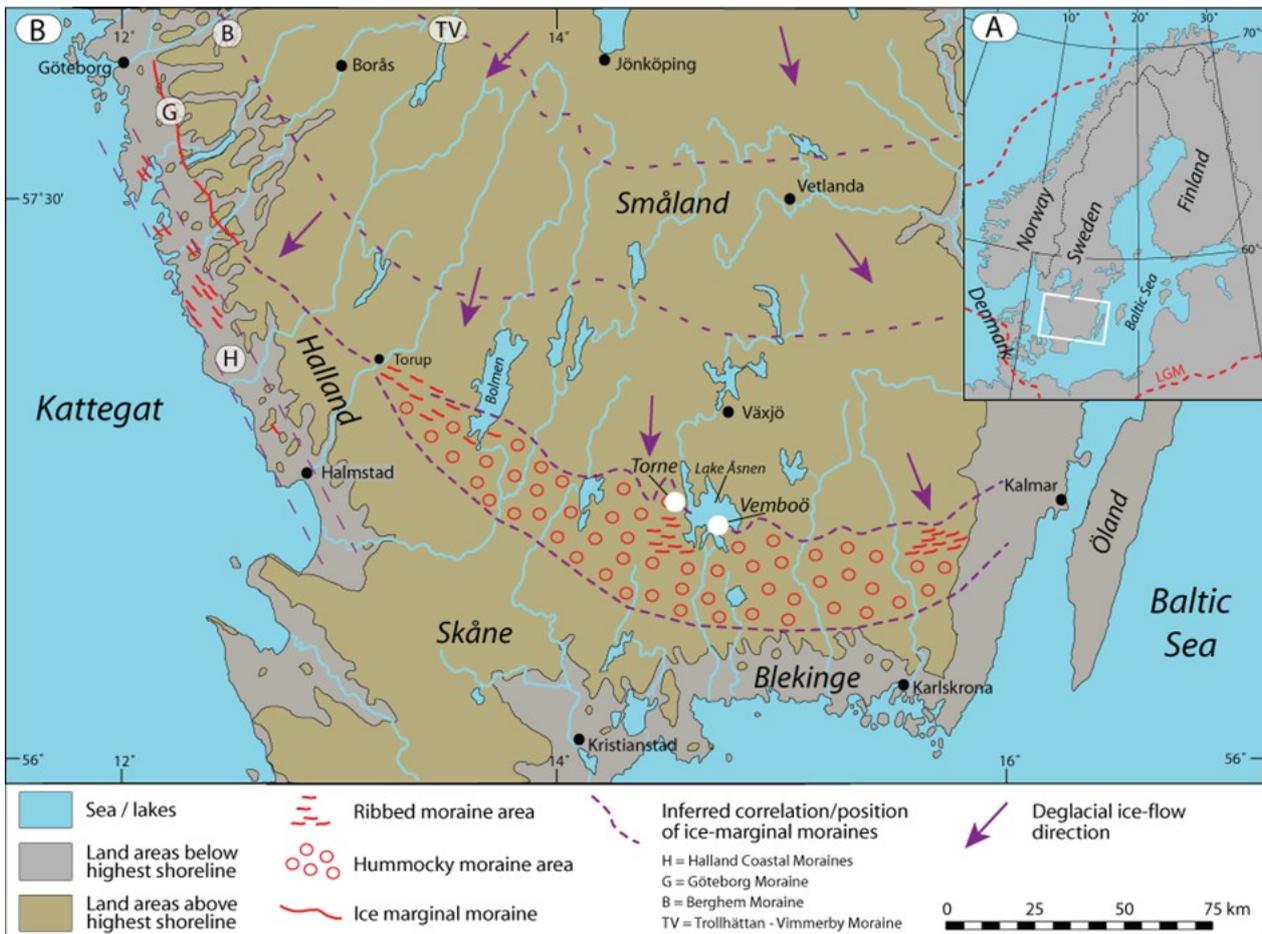


Fig. 1. (A) NW Europe with proposed Fennoscandian Ice Sheet margin at LGM (dashed red line) according to Svendsen et al. (2004). (B) Map of southern Sweden (for location, white box in (A)), showing areas above and below the highest shoreline (marine limit in the west) at deglaciation, and inferred ice-marginal positions according to Lundqvist (2009). The continuation of the Göteborg moraine (G) into a regional coverage of hummocky moraine and ribbed moraine is indicated. North of here the terrain is dominated by streamlined terrain, with most drumlins being of the rock-cored type. Investigated drumlin areas in the Lake Åsnen district are indicated by white dots. Redrawn from Möller (2010).

1.3 Fundamentals of drumlin formations

A drumlin is a subglacially formed landform, belonging to a larger form group or landscape generally described as streamlined terrain. A drumlin ridge can consist of till, sorted sediment or various combinations thereof, and may or may not have a core of bedrock (e.g., Stokes et al. (2011)). Drumlins are commonly found in large groups called swarms. In these swarms the general orientation lays in parallel with each other, and this direction concurs with the former ice flows direction (Benn & Evans 2010; Allaby 2013).

Drumlins are believed to form close to the outer zone of an ice sheet by the deformation of till or sediments through the force provided by the ice movement, likely during a glacial retreat (Allaby 2013). The till located in the upstream part of the drumlin makes up the usually blunt proximal nose and the till downstream from that forms a tail, usually tapering off (Fig. 2). Drumlin swarms in Sweden generally display a high frequency of more or less exposed bedrock, preferentially in the proximal part of the drumlins (e.g., (Möller & Dowling 2015)), and can accordingly be classified as rock-cored drumlins. In some formations the proximal nose is missing, and such drumlins can be classified as crag and tails (Boulton 1987). As will be shown in this paper, the studied drumlin swarms are preferentially of the bedrock-cored type, subglacially formed streamlined formations with a bedrock core. They thus most likely were formed by the depositional processes suggested by Boulton (1982). These processes are summarized below.

The possibly occurring core of drumlins can be divided into three general groups depending on their cores: a bedrock core, a till core, or a core consisting of coarse grained water-lain sediments (Boulton 1982; Boulton 1987). As stated above, in these study areas the principal cores consists of bedrock.

Three different sets of glacial depositional processes are widely recognized in conjunction to drumlins forming around a bedrock core; these are:

- I. Deposition of sediments in cavities, formed in lee-side position with respect to the bedrock-core and ice-flow direction.
- II. Lodgement of debris in traction over the bed.
- III. Deformation of subglacial sediments, that stabilizes (becoming deposited) around bedrock obstructions.

The principal glacial controls that determine if lee-side cavities form, or not, are effective pressure variations over a bedrock knob, the form factor of that bedrock knob (i.e. height divided by length) and basal ice flow velocity (Fig. 3) (Boulton 1982). The cavities that make sediment accumulation possible in lee-side positions are due to a combination of a low pressure zone on the lee-side of a hard core, a high form factor and/or a high ice-flow velocity. When a lee-side cavity is formed, sediments can be trapped there. These depositional processes include *fine slurry* till that enters the cavity from the ice-rock interface (Fig. 4A), melt release of debris from the glacier sole above the cavity roof (Fig. 4B) and decollement of ice from the cavity roof that produces debris-rich 'curls' that will be embedded into other sediments deposited in the cavity, forming 'till balls' (Fig. 4C).

A fourth important sedimentation process in a lee-side cavity is deposition of sorted sediment from melt-water seeking its way into the cavity; these sediments can be from fine-grained silt to coarse sand and gravel of various facies states (Boulton 1987).

In addition to this, the same stress parameters favoring the formation of a lee-side cavity also favors lodgment on the proximal bard of the bedrock knob. This is due to the frictional coefficient between clasts and the bed in the basal transport zone of the glacier is greater than that between the ice and the bed. Therefore clasts erode the bed and lodgment may occur Boulton (1982); (Boulton 1987) also describes a third process, deformation of subglacial sediments, at which drumlins can form due to the stabilization of the deforming bed. When a perfectly homogenous subglacial mass of sediments deform over a smooth plane of decollement, the thickness of the deforming layer will remain constant and flow lines within the sediment are expected to parallel those in the basal ice. But if it's inhomogeneous sediments that deform, the deformation will be determined by the sediments properties,

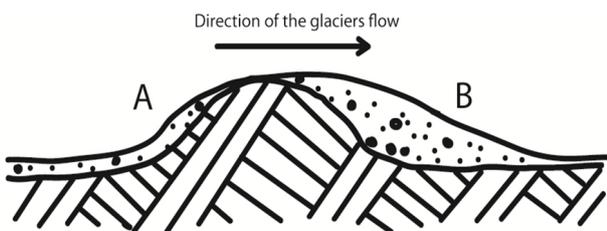


Fig. 2. Principal sketch of a longitudinal section of a rock-cored drumlin with a 'pre-crag' on the stoss side of a bedrock core (A) and a lee-side tail (B), a 'post-crag' in distal direction from the rock core.

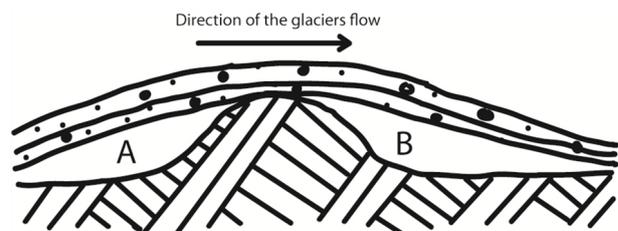


Fig. 3. Principal sketch of a longitudinal section of a rock-cored drumlin with a 'pre-crag' on the stoss side of a bedrock core (A) and a lee-side tail (B), a 'post-crag' in distal direction from the rock core.

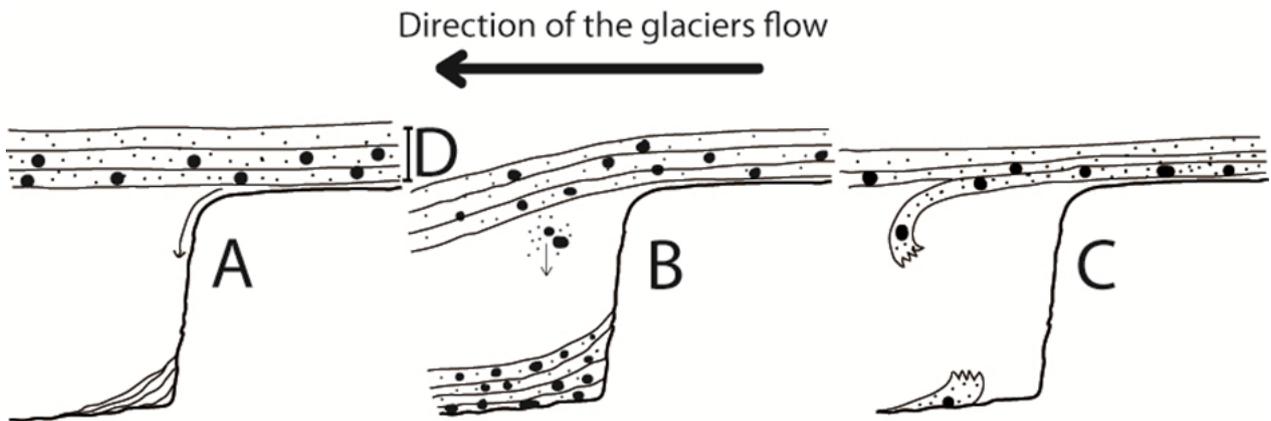


Fig. 4. Lee-side cavity-infill processes producing drumlin tails distal to a bedrock core according to Boulton (1982). For explanation, see text.

such as strength. The process will according to Boulton's model give form to a mobile drumlin formation whose movement is determined by the strength of the sediments. The same factors will produce a static drumlin if the plane of decollement is irregular, e.g. when a bedrock surface locally penetrates the otherwise planar decollement below the deforming sediments. According to Boulton (1987), the deforming layer will form a kind of 'standing wave around such bedrock obstructions to flow, that will stabilize with reduced shear stresses and eventually take the form of a drumlin at deglaciation.

1.4 LiDAR and Digital Elevation Models

Previously there have been two ways of locating drumlins, by analyzing aerial photographs and through field surveys. Both methods lack accuracy for minor landforms, and dense vegetation has been a major problem, especially in heavily forested regions. However, recent advances in technology offer new possibilities to detect subtle, inaccessible landforms (Dowling et al. 2013; Dowling et al. 2015).

LiDAR (*Light Detection and Ranging*) data has been produced by the Swedish National mapping agency (Lantmäteriet; <http://www.lantmateriet.se>) by scanning most of Sweden at a pixel size of c. 2 m and a height resolution at c. 0.1 m (Lantmäteriet 2015). The method involves flying over an area with aircraft whilst scanning the ground with a laser. The return signal can then be analyzed (Fig. 5) to filter out vegetation, tree canopy and manmade structures, showing the so called true ground level. The filtering process to remove obstructions is achieved through a combination of algorithms and manual editing (Gibson 2000). This means that the results, though fairly accurate, might have minor inconsistencies that have to be taken into account. From the LiDAR data very precise *Digital Elevations Models* (DEM's) can be produced, with

hillshade performed from different directions for easy interpretation of landforms.

2 Methods

2.1 Mapping drumlins from Digital Elevation Models

The LiDAR data provided by the Swedish national mapping agency (Lantmäteriet 2015) were used to create hillshaded terrain models, DEM's, for two selected areas in the Lake Åsnen district using the software package ArcGIS10™. Four illumination configurations were applied, with illumination azimuths from 45°, 90°, 180° and 315°, all with an illumination angle set to 20° and vertical exaggeration of 5.

When mapping drumlin features in the DEM's it's important to have criteria's set up (Dowling et al. 2015), enabling consistency and avoiding inaccuracy in the data set. These include a sharp rim and leading point marking the extent of the A (longitudinal) and B (transverse) axes of mapped drumlins. When one streamlined formation overlapped another the extents for each individual drumlin were determined by following their respective rims along their intersection. Mapping of individual drumlins was accomplished by identifying their A- and B-axes in order to get a sense of scope and prevalent directions, thereby enabling the application of a polygon covering the formations area. The mapping process was initiated by charting the major formations. All the azimuths need to be used to verify that no formations are missed. Using this process, more than 450 streamlined formations were mapped over the two study areas, 201 of which were later verified in the field.

Outcropping bedrock was identified by starting at the most obvious examples, thereby gathering experience and working towards the more difficult ones to assess. Drumlins where a bedrock outcrop could be

identified (or suspected) anywhere inside the rim were classified as rock-cored, whereas if no outcrops were identified in the DEM's, the formation was classified as "unknown" core type. The work method is illustrated in Fig 5, and the results with mapped drumlin outlines, long axes, and identified/suspected rock cores are shown in appendices B, C, D and E.

A complication to the process was encountered in that many of the formations with no visible outcrop had superimposed sediments, especially water-lain. Consequently the "true" extent of rock-cores can be difficult to establish. Another difficulty was in sorting out the large amount of cairns and boulders that farmers have dug up and placed around the landscape in both recent and historic times (Appendix A). Both objects can look deceptively much like bedrock outcrops and careful observation of the surrounding environment is required for a high accuracy result.

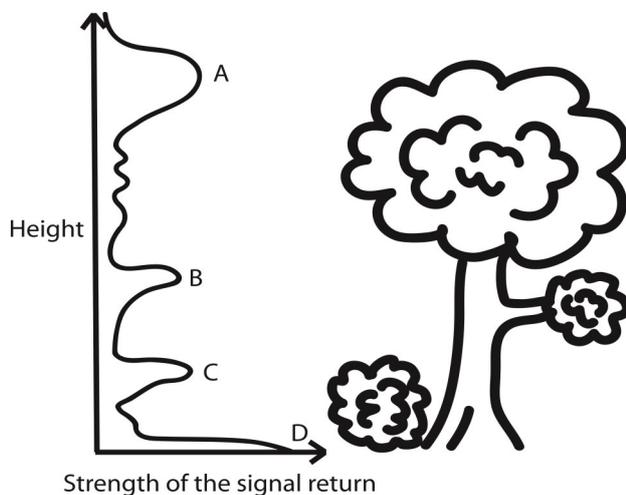


Fig. 5. When a LiDAR scan is carried out a laser is directed towards the ground. The return signals strength is then analyzed to filter out vegetation. (A-C) Represent strong return signals due to reflection from vegetation. (D) Represents the last return that will be registered as the true ground elevation.

3 Results

3.1 Field Survey

Prior to conducting the field verification of mapped drumlins in the DEM's, 207 of the identified drumlins were selected for further studies, 114 in the Vemboö area and 87 in the Torne area (Fig. 1). This selection was done due to time constraints and based on geographical location. Of the 207 drumlins, 201 were possible to visit. On six of them the vegetation was so thick that traversing the area was impossible; therefore these had to be excluded from the dataset. Upon traveling to each drumlin an ocular examination was done and if deemed necessary, a stake was used to penetrate shallow soil in the search for bedrock. This method had to be used with caution due to the large amounts and boulders in the till that might give a false reading.

The boulders in the till also made it precarious to map minor bedrock outcrops where a larger area of knob or scarp wasn't exposed. Therefore searching for signs of the ice eroding the outcrops were important, as such roche moutonnées and fractures were elementary in determining if an object consisted of bedrock or were a large boulder (Appendix A).

Of the 201 drumlins that were field checked, 171 of them were confirmed to contain a bedrock core, while in 30 cases no bedrock could be found. These were therefor classified as belonging to the unknown-core group. The results from DEM bedrock-core mapping and the subsequent field check are summarized in Table 1.

Of the 114 drumlins mapped within the Vemboö area, 105 were found to have a rock core and in 9 cases no bedrock could be identified. The DEM mapping of rock cores failed in only 4 cases, meaning that the field check verified an existing rock core to a 96.3% level. As an end result, 105 (~92%) of the

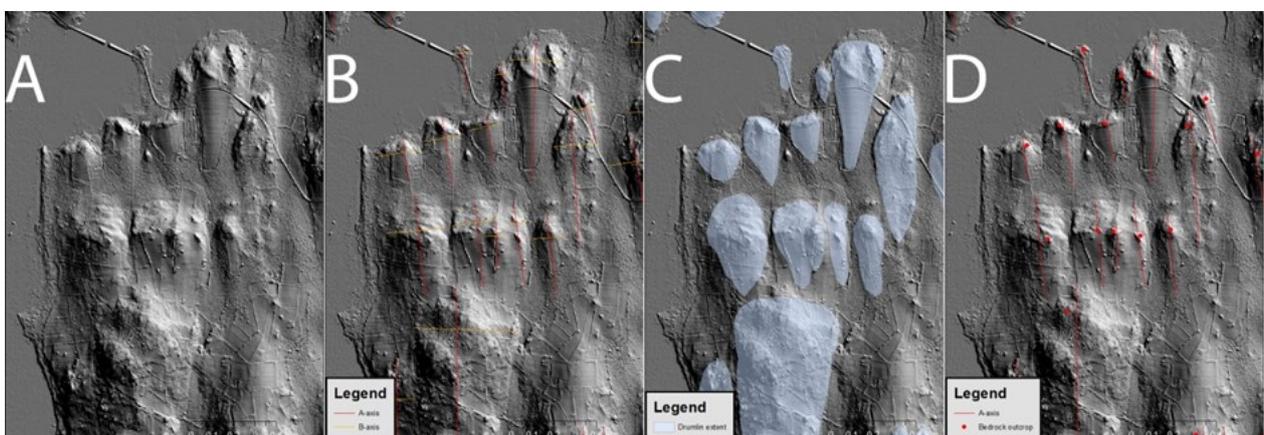


Fig. 6. The work process used when the drumlins were mapped. (A) A hillshade background with the setting azimuth 45°, illumination angle 20° and vertical exaggeration 5. (B) A- and B-axes marked on the DEM (C) A polygon is made to cover the drumlins outer rim, giving the plan form. (D) A-axes of mapped drumlins, with identified/suspected rock outcrops marked with red dots.

Tab. 1. The data over drumlin cores in the areas of Vemboö and Torne summarized.

Lake Åsnen, the Vemboö area	no.	%
Total number of identified drumlins	114	100.0%
LiDAR-identified rock cores	108	94.7%
Field-verified rock cores of above	104	96.3%
LiDAR miss-interpreted rock cores (no core identified in the field)	4	3.5%
Field-identified rock cores without LiDAR identification	1	0.9%
Field-verified drumlins with no visible rock core	9	7.9%
Of the total number of mapped drumlins are:		
Rock-cored	105	92.1%
No visible rock core	9	7.9%
Lake Åsnen, Torne area		
Total number of identified drumlins	87	100.0%
LiDAR-identified rock cores	64	73.6%
Field-verified rock cores of above	63	98.4%
LiDAR miss-interpreted rock cores (no core identified in the field)	1	1.5%
Field-identified rock cores without LiDAR identification	3	3.4%
Field-verified drumlins with no visible rock core	21	24.1%
Of the total number of mapped drumlins are:		
Rock-cored	66	75.9%
No visible rock core	21	24.1%

mapped drumlins were verified to have a rock core and thus confirmed to belong to the hard-core group (Appendices B-C).

Of the 87 drumlins that were mapped within the Torne area, 66 were found to have a rock core and in 21 cases no bedrock could be identified. The DEM mapping of rock cores failed in only 1 case, meaning that the field check verified an existing rock core to a 98.4% level. As an end result, 66 (76%) of the mapped drumlins were verified to have a rock core and thus confirmed to belong to the hard-core group (Appendices D-E).

4 Discussion

4.1 Evaluation of the regional setting and mapping through LiDAR derived hillshade models

The large percentages of drumlins where bedrock was identified strongly supports the conclusion that

drumlins in the Lake Åsnen region predominantly belong to the general drumlin group with hard cores. This means that the three different process scenarios for sediment deposition around rock knobs at the ice-bed interface, described in the introduction (Boulton 1982; 1987) must have had a major role in the formation of the two areas landscape. It is also likely that the drumlins without an identified rock core don't belong to the general groups of till cored or cores consisting of coarse grained water-lain sediments. Instead it is most probable that many, if not all the drumlins classified as unknown-cored, have a hard-core of bedrock that has been superimposed by till or other sediments.

The method used to map the drumlins through DEM's proved to have an overall accuracy of over 95% in identifying rock cores. This result is high enough to conclude that larger areas might be mapped with a high degree of accuracy and without the type of extensive field checks that accompanied this study.

The relatively thin till and thus the high frequency of

bedrock outcrops in the Lake Åsnen district made it easier to identify the outcrops that existed in relation to drumlins; this may not be true for other areas. Something to be wary of in areas similar to the one in this study is large boulders and man-made mounds of boulders; these proved to look deceptively much like bedrock in the DEM's. The only minor difference was a tendency to exhibit small bumps on the surface, which may very well not be visible in lower resolution models and sometime locations. The majority of misinterpreted bedrock out-crops in this study were due to these kinds of objects, sometimes with cairns of rocks and boulders, having been placed in mounds on top of outcrops of bedrock. This problem can be mitigated through familiarity with the area and a more extensive experience in mapping through DEM's.

4.2 Future studies

As for future studies I'd recommend following up on the suspicions that the drumlins in the unknown-core group actually has one that's covered by sediments or till. This could be done using geophysics, as shown in Asani (2015) or through investigating drill logs in the region.

5 Conclusions

The study shows, via analysis of high resolution digital elevation models derived from LiDAR scans and field surveys:

- That 92.1% of all drumlins in the Vemboö area have an identified rock core.
- That 75.9% of all drumlins in the Torne area have an identified rock core.
- The high percentages makes it likely that the remaining drumlins have a rock core at depth that is superimposed by till and other sediments.
- The method of using LiDAR derived digital elevation models to map outcrops of bedrock proved to be correct in more than 95% of the cases. This is high enough to be able to recommend using the method described confidently without the extensive field surveys in this study as a compliment.
- Since the method of identifying formations through DEM's proved accurate and the work process is quick and cheap, it can be recommended for use over a significantly larger area.

6 Acknowledgements

I'm grateful for the helpful counseling and support provided by Per Möller and Tom Dowling, Department of Geology, Lund University, during the work on this paper. The Swedish Science Council, *Vetenskapsrådet*, for making access to the LiDAR derived height models possible to all students and employees at Lund University and, finally, to the hipster farmer who towed our car

up from a muddy field it was mistakenly parked there.

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