The drumlin problem : streamlined subglacial bedforms in southern Sweden

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The drumlin problem

Streamlined subglacial bedforms in southern Sweden

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Abstract

This thesis investigates stream-lined subglacial bedforms (often referred to as drumlins) in southern Sweden. The broad aim of this is to contribute to the solution of the 'drumlin problem'. The term drumlin has come to be applied to a wide range of features whose internal architecture (core) and overall morphology are seen to vary greatly. This range in characteristics is in part responsible for the various competing theories of drumlin formation, each different type of core and morphology generating a new idea for how it came about.

Here the new Swedish national height model, a high resolution LiDAR derived digital elevation model, in combination with detailed sedimentological work is used to characterise streamlined terrain in southern Sweden and investigate the formation processes associated with it.

The findings of this are that drumlinoids in southern Sweden are predominantly rock cored. Soft cored features tend to be significantly longer than rock cored features. In general, drumlinoids in southern Sweden are located at the lower end of the size spectrum in terms of global streamlined sub-glacial features. Additionally it has been found that drumlinoids can form rapidly at glacial margins as well as within the main body of ice sheets. And finally, the most important contextual geological factor in drumlinoid parameter (morphology) formation appears to be drift depth/properties. The bedrock type beneath a feature and the hydrological system as recorded in eskers do play a role, but the exact nature of this is not certain and the correlations are difficult to analyse.

In addition to these findings a generalised conceptual model of drumlinoid formation is proposed and a discussion of the possible ways in which physical processes influence said formation is offered. It is suggested that chaotic behaviour and the role of scale might be useful to consider and that whilst it is something of semantic point, the use of the term drumlinoid is deliberate and important. This is because due to equifinality there are many landforms that researchers can split into different categories, e.g. rock drumlins, clone drumlins, emergent drumlinds, downwards emergent drumlins or obstacle drumlins. These are all valid divisions as there are different physical processes involved in their formation. However these processes and the final landforms that result from them are all part of the sub-glacial continuum and so at one level must be considered part of the same family.

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For my parents, sorry about all the noise.

"He wasn't strictly aware of it, but he treated even geography as if he was investigating a crime (did you see who carved out the valley? Would you recognize that glacier if you saw it again?)" - The Fifth Elephant - Terry Pratchett

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T.P.F. Dowling, H. Alexanderson & P. Möller (2013). The new high-resolution LiDAR digital height model ('Ny Nationell Höjdmodell') and its application to Swedish Quaternary geomorphology, GFF, 135 (2), 145-151.

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Paper II

T.P.F. Dowling, M. Spagnolo & P. Möller (2015). Morphometry and core type of streamlined bedforms in southern Sweden from high resolution LiDAR, Geomorphology, 236, 54-63. Reprinted with permission of Elsevier.

Paper III

T.P.F. Dowling, P. Möller, S. Greenwood, M. Spagnolo, M. Åkesson, S. Fraser, A. Hughs & C. Clark (manuscript). The extent to which geological factors influence the shape of streamlined subglacial bedforms.

Paper IV

P. Möller & T.P.F. Dowling (2015). The importance of thermal boundary transitions on glacial geomorphology; mapping of ribbed/hummocky moraine and streamlined terrain from LiDAR, over Småland, South Sweden, GFF, 1-32.

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Paper V

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Paper VI

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Thanks to my family I am where I am today. Thank you for not rolling your eyes too much every time I go off on one about geology/geography. Thanks for always being there.

It is not an exaggeration to say that this work would not have been completed without the support of my friends. A PhD has many (many) ups and downs, through it all friends near and far have kept me going with fika, cake and when necessary… gin/mojito. I cannot name you all individually here for which I apologise, however I must mention some leading characters: Carolina- your calm words of advice , supply of tea and constant friendship kept me going through the worst and made the best even better. Patrick and Wim, sorry to lump you together but in the end you both survived living three years with me, together, so that must count for something! Patrick- your 'helpful' comments never failed to amuse. Wim- I still remember with gratitude your care when you found me collapsed on a couch with a freshly dislocated shoulder. I wish you both the best with your next great adventure. Laurie- late to party but what an impact! Food, dancing and rum are an unbeatable combination that I look forward to more of in your company. Florian (A)- you were the poor soul who was assigned to be my mentor, something that you have done ably and with just the right degree of sarcasm. Thanks for helping with so many things, Matlab in particular! Maira (Å)- thanks for the fika, the dinners, the cosy home parties and SOM'spiration! Guillemet/Guillame/Guillaume(??)- thanks for the never ending cheerfulness, always up for a beer and providing just the right amount of 'je ne sais quoi'. Emma (L)- team drumlin! You came on-board the fieldwork as a friend and left as a great friend. The fact that we are still friends despite clast fabric analyses says a lot I feel.

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Last, but by no means least, Emma. Thank you, for everything.

Scope of Thesis

The general aim of this thesis is to investigate 'the drumlin problem', primarily using datasets and field investigations from southern Sweden. Or in other words; how do drumlins form and why? The specific aims of the thesis are to investigate the following:

- What are the characteristics of streamlined sub-glacial bedforms (also known as drumlins) in southern Sweden?
- How does the geological and geographical context in which streamlined sub-glacial bedforms evolve affect their formation processes?

Introduction

The 'drumlin problem' is one that has vexed scientists for well over 100 years (Stokes et al., 2011). But what is a drumlin? And what is their problem?

A drumlin, the name originating from the Gaelic 'druim' (rounded hill, Fig. 1), is classically defined as 'typically smooth, oval shaped hills of glacial drift resembling in morphology an inverted spoon or an egg half buried along its long axis. Generally the steep, blunter, end points in the up-ice direction and the gentler sloping pointed end faces in the down-ice direction, these two ends being known as the stoss and lee sides respectively' (Menzies, 1979; c.f. Benn and Evans, 2010, p. 451). However this classical definition fails to capture the wide range of both drumlin shape (morphology) and internal sediments (core) that are found in formally glaciated regions across the world (Spagnolo et al., 2010; Stokes et al., 2011). Due to this, the term 'drumlin' has come to be applied to a host of features, whose internal sediments and external expression are seen to vary greatly. This range in characteristics is in part responsible for the various competing theories of drumlin formation, each different type of core and morphology generating a new idea for how it came about. A further complication is that drumlins form beneath ice sheets, this means that it is very difficult to observe the landforms as they are created. The only two exceptions to this are the observations from beneath an Antarctic ice stream by King et al., (2007) and the recently described emerging drumlin field at Múlajökull, Iceland (Johnson et al., 2010).

Fig.1 Drumlins; two examples indicated by white arrows. Located on the west coast of Ireland, image ©Michael Gibbons 2015. Source: http://walkingireland.com/wp-content/uploads/2013/06/Drumlins-from-the-air.jpg.

To avoid the semantic pitfalls inherent in the drumlin formation debate caused by the above, the landforms under investigation here will be referred to as 'streamlined sub-glacial bedforms' or 'drumlinoids'. By using this terminology it is made explicit that no prior judgement is made as to formation process and that all streamlined subglacial bedforms, with one exception that is detailed later, are included.

The morphology of drumlinoids forms a size and shape continuum that has led many to conclude that they must have been formed by one process or are subject to an overriding process that controls their final size and shape characteristics distribution (Clark et al., 2009; Hillier et al., 2013). Drumlinoids can vary in size from a few meters in all dimensions up to kilometers in length and width. However these larger forms are very rare and the majority of features are within the tens to hundreds of meters range (e.g. Hughes et al., 2010; Spagnolo et al., 2011; Spagnolo et al., 2012; Dowling et al., 2015). Researchers have traditionally defined a drumlinoid within the landscape by outlining the break of slope around the base of a feature and from this defining their length, width, height and elongation ratio (length divided by width). By its very nature this method of defining an object excludes the landscape in which the feature actually sits. In particular the negative space between drumlinoids is left out of the analysis. Some work is starting to look at this problem by bringing in whole-landscape concepts from aeolian geomorphology and re-examining the ontology of how glacial geomorphologists consider the features under investigation. However, due to the very recent nature of these developments, for the purposes of this thesis the traditional method of delineation is used. But we use this method with the aim of including the rest of the landscape through other means. Examples of the wide variety of drumlinoid form seen in the Swedish dataset are provided in Fig. 2.

As stated above, the internal sediments (core) of drumlinoids can vary greatly. Stokes et al. (2011) examined this aspect of the problem and provided a five part generalised descriptive classification for the organisation of the internal architecture (Fig. 3). The formation processes of purely bedrock features (type 1) are well known and consequently these features are often placed in a separate cat-

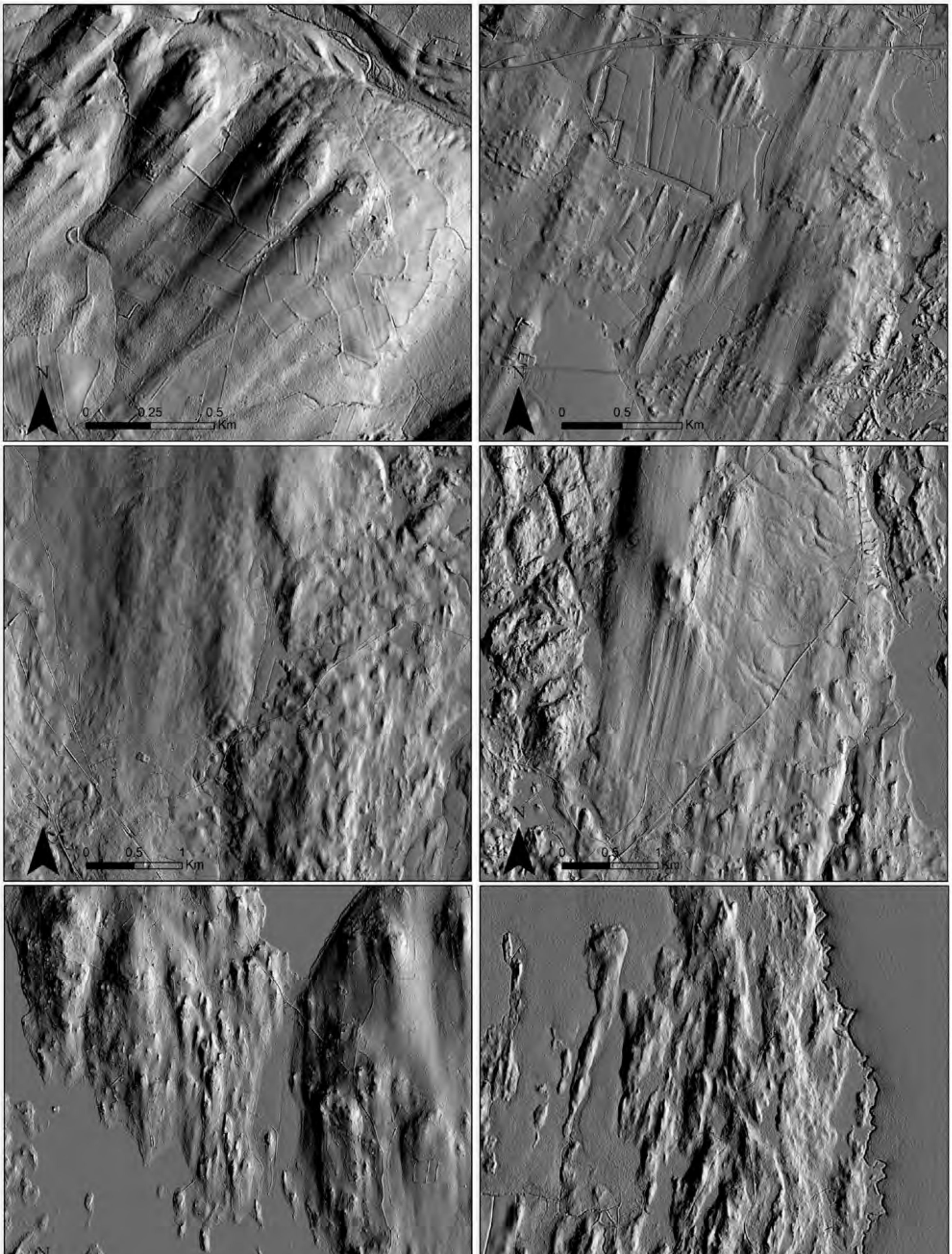

Fig. 2 Examples of drumlinoids in their natural habitiat. Images are generated from the 2 m resolution Swedish national height model- the height data is hill-shaded with illumination azimuth at at 90°, alitude at 25° and a x5 vertical exageration. These images are taken from southern Swedish region and illustrate the range in shape and size found.

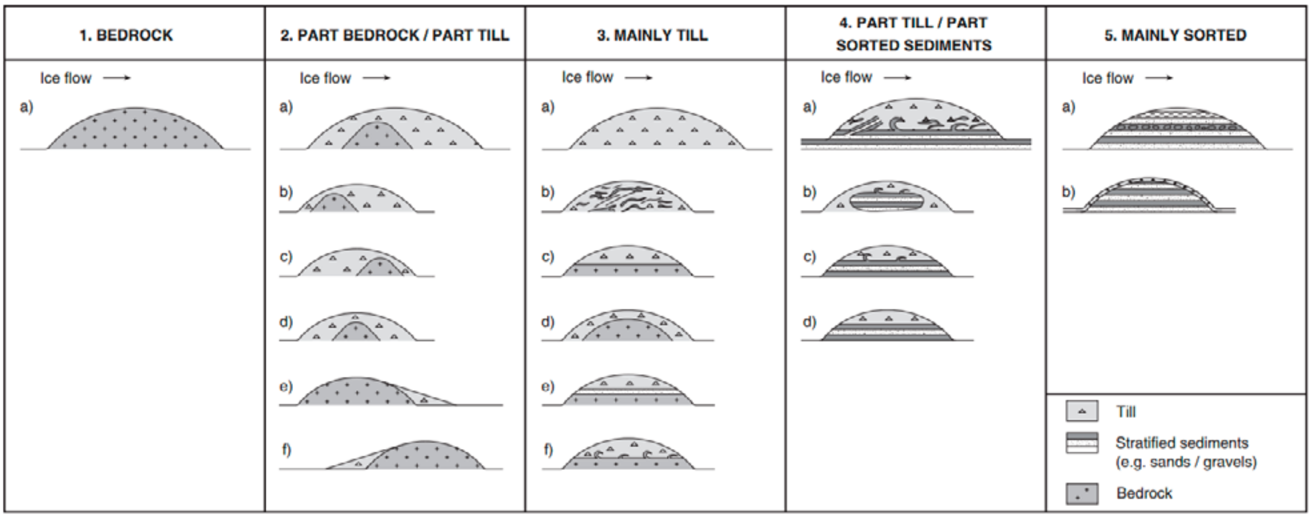

Fig. 3 The five types of internal streamlined bedform organisation. Reproduced from Stokes, et al. (2011).

egory called rock drumlins (roche moutonnée) (Roberts and Long, 2005; Glückert, 1973). Therefore whilst these features are drumlin like in their shape, for the purposes of the drumlin problem as investigated here they are not considered drumlinoids and are not part of the datasets. This is due the lack of unconsolidated sediments in their form.

The part bedrock/part till internal type (2) drumlinoids are commonly referred to as 'rock cored' and have been labelled by many in the past as 'crag and tails' when the rock core is at the stoss end of the landform (e.g. Evans and Hansom, 1996; Jansson and Kleman, 1999). The crag and tail label is not used here as the position of the rock core is found to vary greatly throughout the Swedish dataset (Möller, 1987; Dowling et al., 2015). Clark (2010) names this sort of feature an 'obstacle drumlin' in recognition of this. The formation of these obstacle drumlins has typically been considered relatively easy to explain by the deformation and plastering on of sediment around the obstacle combined with the filling of a downstream cavity formed in the ice by the pressure shadow generated by said obstacle (Hart, 1997). A part of this process is also likely to be the capture of deforming drift patches around bedrock knobs or along rock escarpments (Boulton, 1987). Whilst the exact mechanism of sediment inflow into cavities is still a subject of debate in some quarters (e.g. Shaw, 2010; Clerc et al., 2012 Piotrowski, 2013), for the most part the role of a bedrock obstacle in bedform formation is not the subject of debate. One area in which there is perhaps a lack of detailed research is the existence of the so called 'pre-crag' variant (Haavisto-Hyvärinen, 1997). This is where sediment has accumulated on the stoss side of the bedrock core and generated a tail that points up-ice rather than down ice (Fig. 4). Whilst slow ice flow with little cavitation is invoked to explain this (Stokes et al., 2013), the long forms seen in the Swedish dataset do not fit this explanation quite so easily. Overall, whilst obstacle drumlinoids are part of the drumlin problem, they are perhaps the least problematical landforms that are a part of the conundrum.

On the other hand the remaining three types are most definitely the crux of the problem. All three are composed of unconsolidated sediments and so are referred to as 'soft cored'. At one end of the scale there are mainly till features that can be formed of a homogenous mass of till or deformed layers of multiple tills (type 3). At the other end of the scale there are drumlinoids that consist entirely of undisturbed stratified sediments, perhaps covered with a thin till carapace (type 5). Between these two end members there are features that are formed partly of till and partly of sorted sediments that may have been deformed or not preserved intact (type 4). These have been termed emergent drumlins in the case of purely till forms and clone drumlins in the case of mainly sorted sediment forms by Clark (2010), with others applying the term 'remnant' (Colgan and Mickelson, 1997; Shaw, 2010) when they consider the main formation processes to be erosive. It is these landforms that are the focus of the drumlin problem.

Why does a continuum of morphology contain such a variety of sedimentology? Why does the resulting external shape form a continuum in the first place? And if they are formed through a variety of processes, why do they form the said continuum? Or if they are formed by one process why does it not act in the same way upon all of the sediments in terms of deforming them or preserving them?

A part of the answer to this problem was provided by Hart (1997) when she categorised the internal sediments of drumlins into three types based on the processes that could be shown to have affected them: 1) depositional, 2) erosional and 3) deformational. Importantly she notes that a drumlinoid can be formed by one process, two processes in combination or an amalgamation of all three. By defining drumlinoids in terms of the formation processes that moulded the sediments we start to move beyond categorisation based purely on a basic observation of form and core towards a more widely applicable process-form

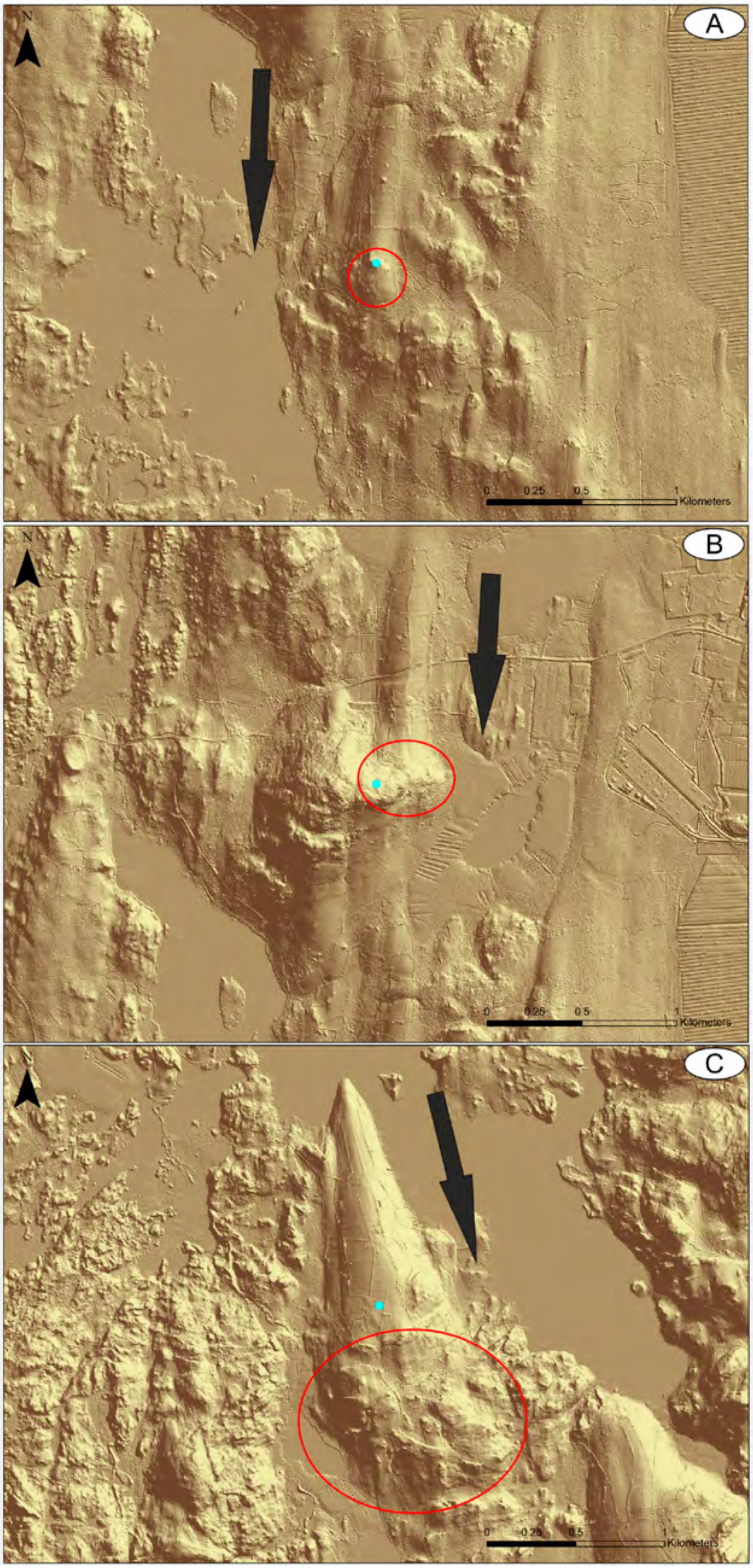

Fig. 4. Examples of reverse crag drumlinoids in the Swedish dataset. Large black arrows indicate the regional ice-flow direction. Red circles indicate the general location of the known bedrock outcrop/core. Blue points are the GIS record of feature location. Panel (A) displays a typical reverse crag feature, surrounded by both smaller and similar size rock cored feaures. Panel (B) Illustrates a particularly odd example, pre and post- crag features are located essentially on the same bedrock knob. Panel (C) shows an example of a particularly large feature, both in terms of width, seemingly controlled by the size of the bedrock outcrop, and length. Illumination azimuth at at 90°, alitude at 25° and a x5 vertical exageration.

model. Whilst this does not constitute a full theory of formation, it creates a framework for examining the problem in greater detail and developing a comprehensive model of drumlinoid formation.

The key concept behind Hart's framework is that drumlinoid initiation is largely dependent on the presence of a core, but once initiation has taken place the subsequent processes are not certain. It is the mix of the three general processes, as set out by Hart (1997), that result in the final architecture and internal composition of any given drumlinoid. The final morphology should be dependent on the combination of: rheology of the drift, the local geological conditions, glacio-hydrological system conditions and the properties of the flowing ice.

(i) Deformation (box 1): in marginal areas that typically have a thin deforming layer, a large influx of sediment will result in constructional deformation (Hart and Smith, 1997; Boulton et al., 2001). Away from the margin, where a thicker deforming layer may be more common, the deforming layer will cut down into pre-existing sediments should more sediment be input, resulting in excavational deformation (Hart, 1997; Hindmarsh, 1999). Boulton (1987) provides a qualitative theory of drumlin formation by deformation that seems to works well for this scenario.

(ii) Erosion: if there is low to negative sediment input into a region then erosive processes take over and the drumlinoid landscape is shaped by the removal of material rather than the input of it (Boyce and Eyles, 1991; Hart, 1997). This could be either in terms of a net erosive deforming sediment bed (Fowler, 1994; Hart, 1995; O'Brien and

Box 1: sediment deformation at the glacier bed

It was not recognised until the early 1980s that active glaciers do not just slide over rocky beds and deform within their own mass (Boulton and Jones, 1979), but that they also flow due to deforming soft sediments that interface with the ice above them. This interface plays an important role in the flow of ice as part of a coupled ice-bed system (Boulton, 1987; Hindmarsh, 1997). The unconsolidated sediments found beneath glaciers are often referred to as tills or glacial diamictons; it is the manner in which these sediments react to the over-riding ice that has provided much material for the drumlin problem. The table below, taken from Evans et al. (2006a), summarises the key characteristics of glacial diamictons, illustrating how changes in water content, pressure, rheology, deformation and internal structures interplay to modify the behaviour of these sedimentary units. When this variability in properties is combined with the variations in glacial properties and subsequent till deformation seen throughout space, as shown in Fig A, it starts to become evident why the internal sediments of even purely till cored drumlins can vary so much. The style of till deformation within drumlinoid formation seen at any given point in time will vary depending on the properties illustrated here as dictated by the relative position within the ice sheet and the rheology of the till.

Phase	Solid state	Semi-solid state	Plastic state	Liquid state	Suspension
Water	Low water content	Increase water content →			Very high water content
Limits	Dry	Shrinkage limit	Plastic limit	Liquid limit	
Shrinkage	Increase in volume →				
Shear strength	Decreasing shear strength →			Negligible to nil	
Till horizon	B	A/B	A		
Dilation	Non dilatant (solid)	Increase in dilation →			
Deformation	Solid state deformation	Solid state/soft sediment deformation	Mobile zone 'flow displacement'	Decoupling/basal sliding	
Structures	Ductile/brittle faults, folds	Ductile folding, shear zones, clast rotation, boudinage, disharmonic folding, convolutions, flame structures	Clast rotation, initiation of sediment mixing/ homogenisation and overprinting of pre-existing structures, no solid state deformation, on set of localised liquefaction at higher water contents	Liquefaction, homogenisation and overprinting of all pre-existing structures, clast rotation, no solid state deformation, injection features into adjacent sediments	

Evans, et al. (2006a) summary of the geotechincal properties and behaviour of glacial diamictons.

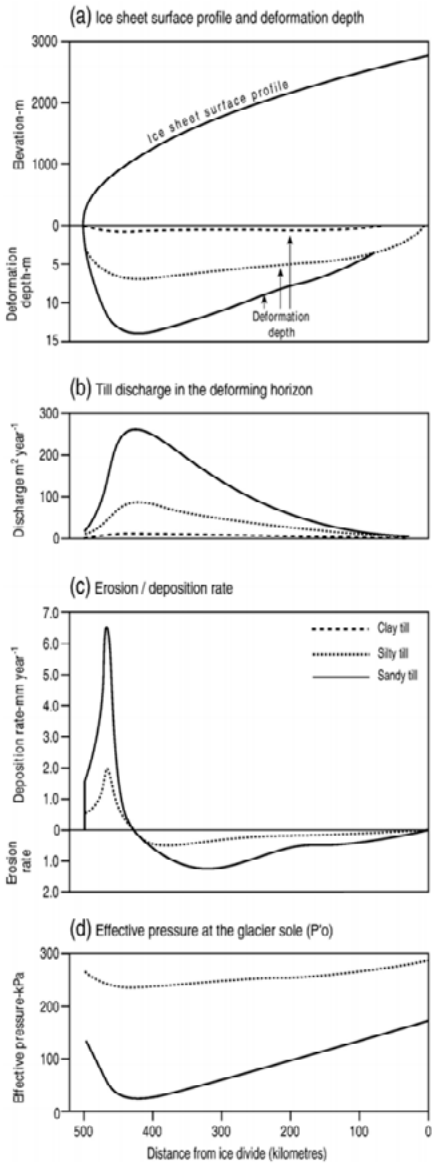

Fig. A. Theoretical conditions at the base of a steady state glacier underlain by a deformable bed. Reproduced from Boulton, 1996, c.f. Evans, et al (2006a).

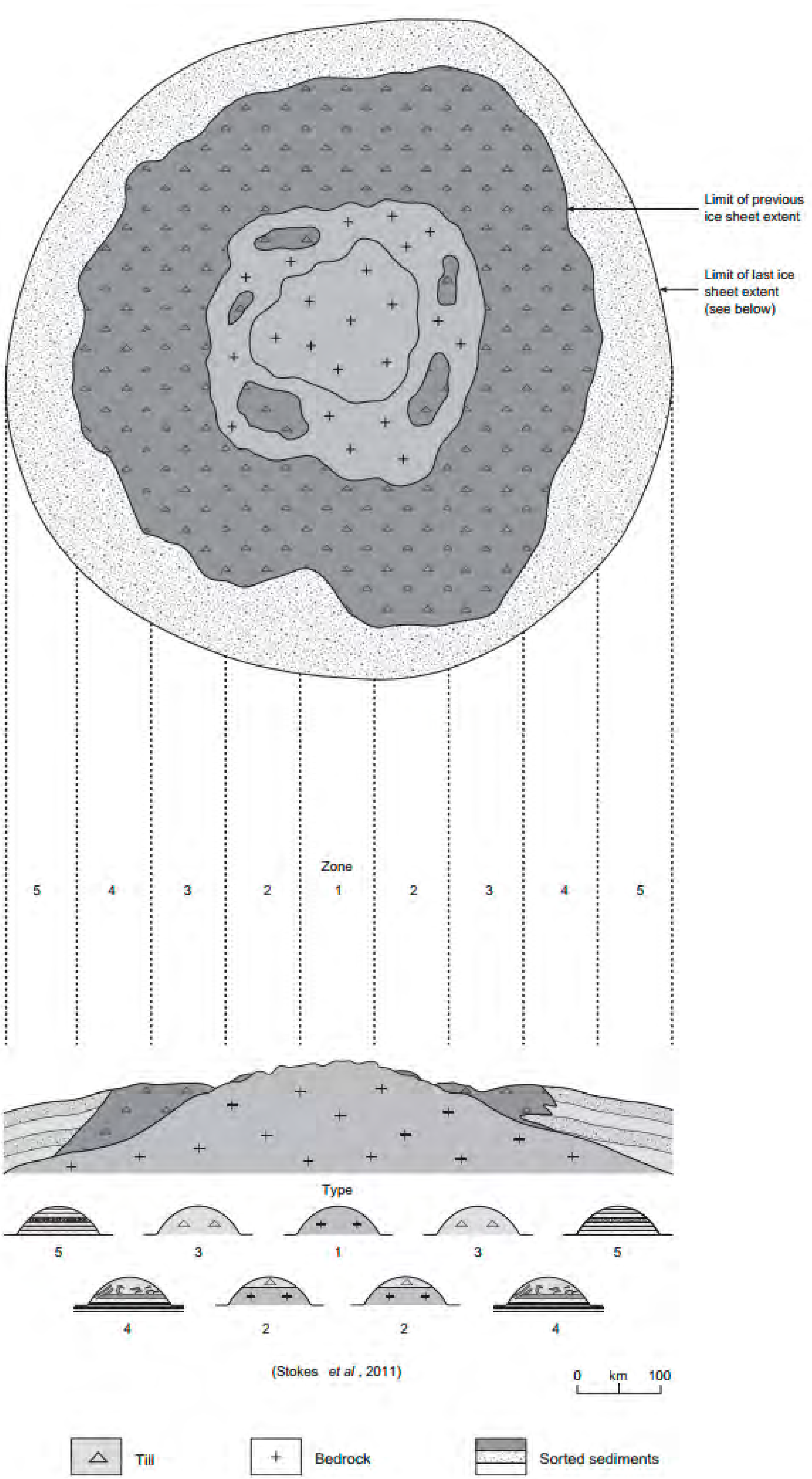

Fig. 5 Stokes, et al. (2013) predicted occurrence of drumlinoid internal architecture under an idealised ice sheet.

Harris, 1996; Eyles, et al. in press), in which case there is a blurring of the line between this category and excavational deformation. Erosion could also perhaps be achieved via steady state subglacial drainage (Eyles, 2006) or in more dramatic fashion via the release of stored meltwater in floods (Fiore et al., 2002). However, it is noted that there is a difference between the plausibility of short term, valley based, flood formation and formation due to catastrophic meltwater release at a continental ice sheet scale (Evans et al., 2006b; Evans, 2010; Shaw, 2010).

(iii) Deposition: Depositional processes can also take place alongside any of these processes. This can be in the form of cavity infilling should a cavity form behind the obstacle as it is developed into a drumlinoid (Dardis and Hanvey, 1994; Linden et al., 2008); or via the plastering (lodgement), folding and stacking of sediment onto and around the core (Boulton et al., 2001). In opposition to this the inter-drumlin areas could be zones of faster flow/deformation/fluvial channels, to the extent that erosion takes place in the troughs whilst deposition takes place on the drumlinoid core (Boyce and Eyles, 1991).

It is thus proposed that the overall streamlined shape of the subsequent landforms is dictated by the flow of ice over the sediments, whilst the internal composition of the drumlinoid is controlled by the combination of initial nucleation point type and the subsequent processes that take place around this core.

However this still leaves the question of why do drumlinoids arise on a flat, homogenous surface that does not contain any patches of stiffer sediment? Leaving aside the possibility that patches of stiffer sediment/patches of deforming sediment could be generated in otherwise homogenous beds by variations in both sub-glacial processes and processes at the ice-air interface (Alley, 1993; Piotrowski et al., 2004; Saks et al., 2012). It has been suggested that the mechanism of flow instability could be a viable explanation (Fowler, 1998; Clark, 2010; Chapwanya et al., 2011; Hooke and Medford, 2013; Stokes et al., 2013; Fowler and Chapwanya, 2014).

An instability mechanism is the means by which small disturbances are amplified through positive feedback to become large (Stokes et al., 2013). This is a fundamental mechanism that is well known in the fluvial and aeolian environments (Chapwanya et al., 2011). Whilst the flow of ice does not behave in the same manner as water or air, it has been shown that it is feasible for such instabilities to be generated at the ice-bed interface and propagated. Both pressure and thermic differentials have been proposed as means to generate the initial points for instability to grow from (e.g. Schoof, 2007; Hooke and Medford, 2013). Attempts at numerically modelling instability generation at the ice-bed interface have thus far succeeded in reliably producing ribbed moraine, but still struggle to transition from ribbed moraine through to fully three dimensional streamlined bedforms. Progress is however being made on this front that suggests that an instability mechanism is very likely to be the answer to drumlinoid emergence on homogenous surfaces (Stokes et al., 2013; Fowler and Chapwanya, 2014).

Based on their proposition that instability theory can explain the majority of drumlinoids, which will be taken up further in the discussion, Stokes et al. (2013) produce a schematic of predicted drumlin occurrence (Fig. 5). This schematic highlights how different drumlinoid core types may form due to their relative position within an ice sheet and the nature of the pre-existing sediments over which the ice sheet flows. If we combine the general idea of the Stokes et al. (2013) (Fig. 5), the process framework set out by Hart (1997) and developments in instability theory for drumlinoid formation on a flat plane, it might reasonably be said that the 'drumlin problem' has effectively been solved in terms of a general conceptual model that can account for the variety of form and shape seen and the internal variability of core type.

However, what remains unknown is the relative contribution of all of the possible geological and glaciological controlling factors to the drumlinoid forming processes. If it is possible to define and numerate how the streamlining behaviour of ice is modulated by the pre-existing sediments and bedrock over which it flows, then drumlinoids could start to be used to reconstruct past ice flow. In particular paleo-reconstructions could start to move beyond an 'it went this way, probably quickly' approach, towards specific rates of ice flow and behaviour. In turn this would allow paleo-reconstructions to better inform numerical ice models of how the flow of ice has reacted to its bed in the past and therefore how it may do so in the future of a changing climate.

Study Sites and Regional Overview

The primary study sites (Fig. 6) for this thesis are located in southern Sweden, with datasets from Britain and Ireland featuring in Paper III. All three of these regions were covered by the Eurasian ice sheet at the time of the last glacial maximum (LGM), ~26,500 – 22,000 years ago (Svendsen et al., 2004) (Fig. 7), maintaining at times separated, and at others conjoined, ice-sheets through this period until the late glacial maximum and subsequent deglaciation ~13,000 -10,000 years ago. A detailed overview of the British and Irish ice sheets is not given here as the primary focus of this thesis is streamlined sub-glacial bedforms in Sweden. For an account of the bedforms of the British ice sheet the reader is referred to Hughes et al. (2014), for the Irish ice sheet to Greenwood and Clark, (2009a)/Greenwood and Clark (2009b) and for an overview of both the British and Irish ice sheets at the LGM

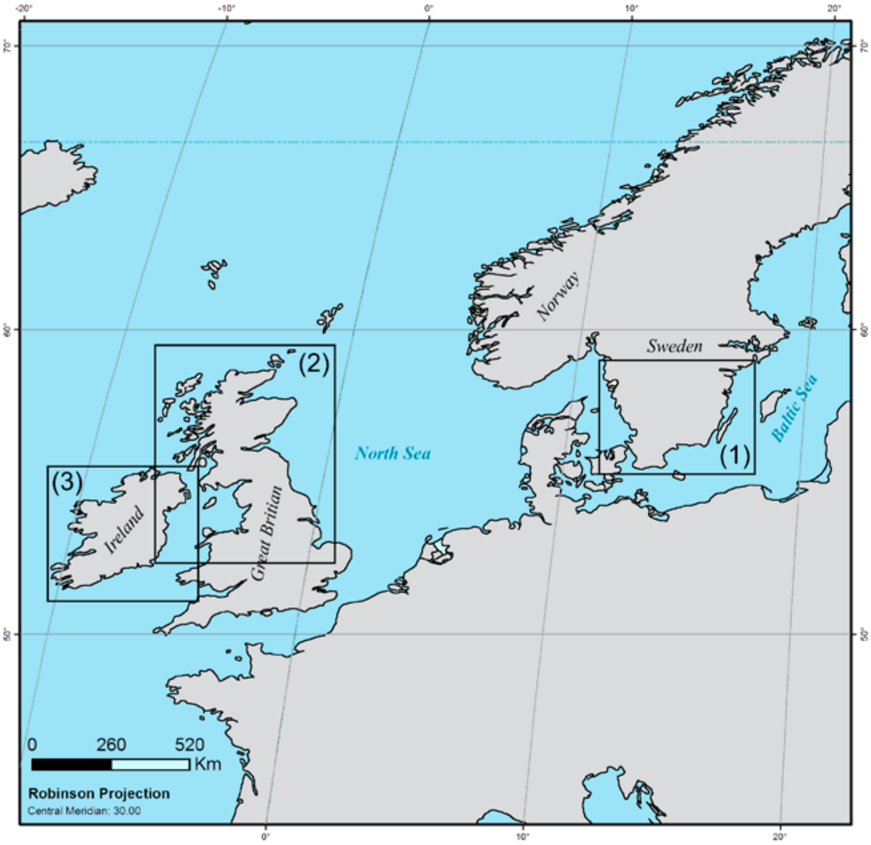

Fig. 6. Location of study areas in the context of north-west Europe. (1) Southern Swedish study area. (2) British study area. (3) Irish study area. Base mapping is ©ESRI, modified and re-drawn from ESRI ArcGIS template 'Europe'.

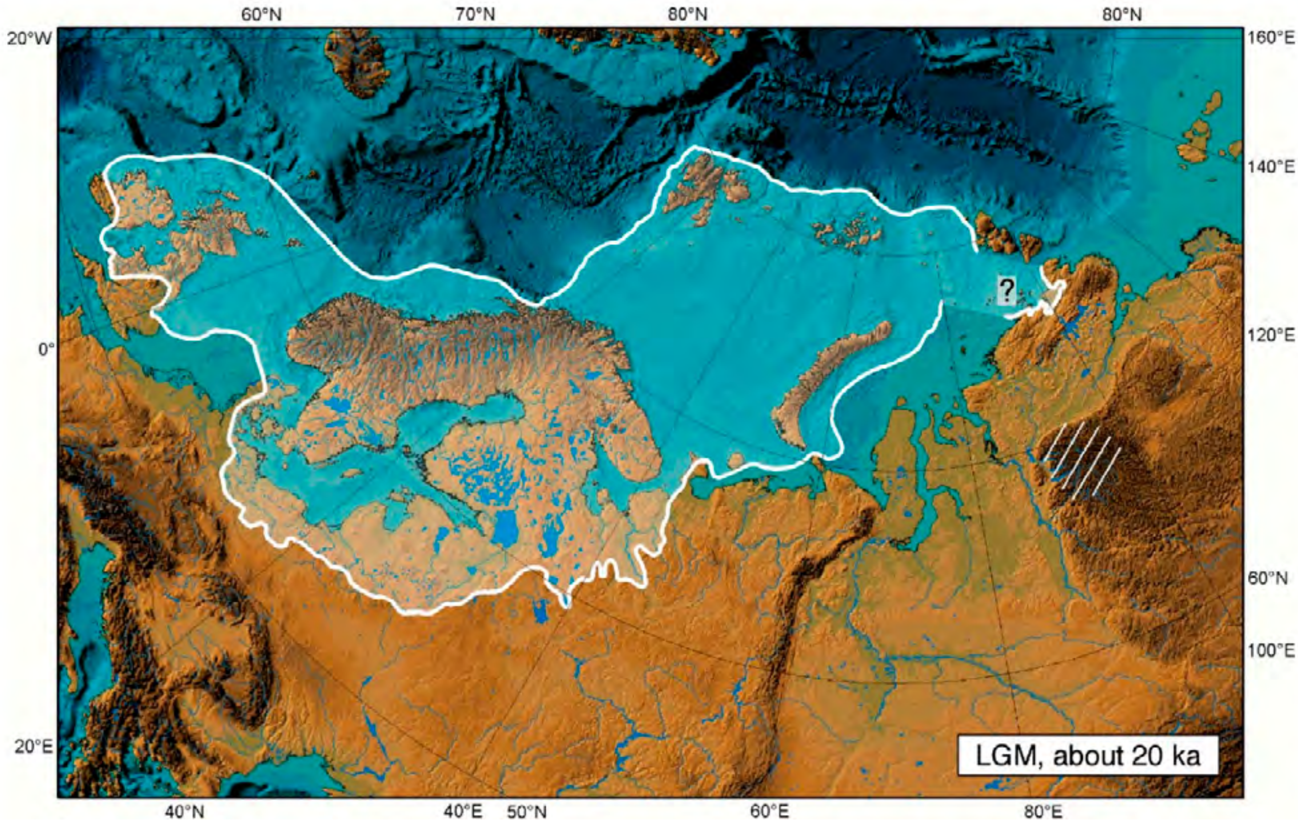

Fig. 7 Extent of the Eurasian ice sheet during the last glacial maximum (LGM) 20,000 years ago, reproduced from Svendsen et al. (2004).

to Chiverrell and Thomas (2010).

The Swedish study area is located in the ice-dynamic sectors 'Southern Sweden' as defined by Stroeven et al. (2015) and the southern part of the sector 'Central Sweden and southeastern Norway' as termed elsewhere (Arnold and Sharp, 2002) (Fig. 8). Stroeven et al. (2015) describe the ice marginal retreat in this sectors as mostly terrestrial and wet based. However this is somewhat

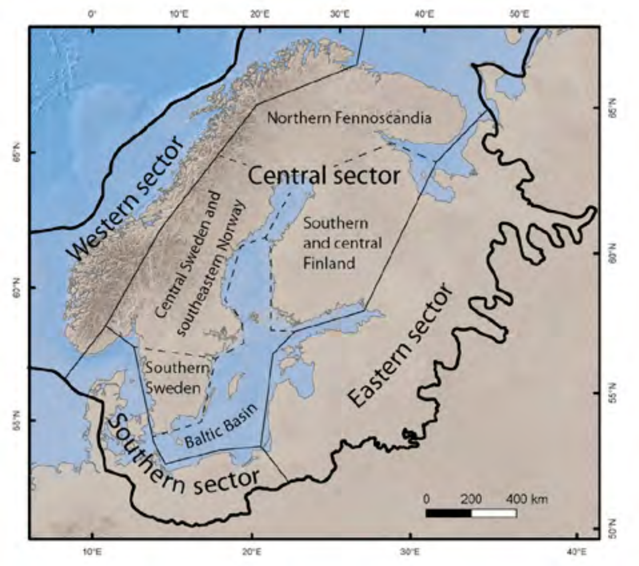

Fig. 8 Ice dynamic divisions of the Fennoscandian ice-sheet, reproduced from Stroeven et al. (2015).

oversimplified: large parts of the southern Sweden sector experienced inundation of water up to the highest shoreline at deglacatiaton, in the west by the sea and in the east by the fresh-water Baltic Ice Lake. Further north the ice margin receded in the Yoldia Sea, connected to North Sea, and later after uplift of this area to the Baltic basin fresh-water Ancylus Lake (Björck and Digerfeldt, 1991; Lundqvist, 1992; Björck, 1995, Mangerud et al., 2004). Thus the large parts of south Sweden below the highest shoreline at deglaciation experienced a subaqueous ice retreat. The generalised bedrock geology of the Swedish area can be split into three main regions (Fredén, 2009). The eastern half of the area consists for the most part of Småland–Värmland granites and acidic volcanic rocks from the Transscandinavian Granite–Porphyry belt. The western part of the study area is formed of the granite and the orthogneiss of SW Sweden. The southernmost section of the study area, SW Skåne, consists of Phanerozoic limestone, shales, and sandstones. For a more detailed breakdown of the bedrock geology see Fig. 9. The various rock types are grouped together into eight simplified categories which are presented in Table 1.

The type of Quaternary sediments overlying the area is highly dependent on location relative to the highest shoreline, which is at about 65 metres above sea level (m asl) in Blekinge and rising to c. 150 m asl in Östergötland (Fig. 10) (Fredén, 2009). Below the highest shoreline a mixture of subglacial tills combined with glaciomarine (the west coast) and glaciolacustrine (Baltic basin in the east) silts and clays predominate, with proglacial glaciofluvial deposits. These are usually emplaced in topographically controlled areas such as inter-drumlin troughs. Above the highest shoreline is a mixture of various types of basal till and stagnant ice features. The thickness of this till varies between mostly scoured bedrock with thin, patchy drift through to intermediate depth tills (Kleman et al., 2008) with the occasional small area of deep drift (Fig. 11). Visible in Fig. 11 are long, thin, deposits of deeper till, in particular flowing south of Lake Värnern.

Esker networks are a common feature, often found close to areas of streamlining that they bound but rarely cut across. Another of the commonly seen surface bedforms

Description	*Code*
Mafic rocks (Silica oversaturated), which are coarse-grained (plutonic), some metamorphosed, some not, exposure is not usually good.	MaF
Felsic rocks (Silica under saturated), which are coarse-grained (plutonic), some metamorphosed, some not, good exposure.	FeP
Mafic rocks (Silica oversaturated), which are fine-grained (volcanic), some metamorphosed, some not, exposure is usually very bad.	MaV
Felsic rocks (Silica under saturated), which are fine-grained (volcanic), some metamorphosed, some not, exposure can be variable.	FeV
Fine-grained clastic sedimentary rocks, prone to weathering, even if metamorphosed, little outcropping.	Fse
Chemical sedimentary rock, prone to chemical weathering, forming sinkholes, little outcrop unless deformed.	Lim
Coarse-grained clastic sedimentary rocks, less prone to weathering, variable exposure.	Cse
Very hard metamorphosed clastic sedimentary rock, very resistant to weathering, good outcrop.	Qua

Table 1. Bedrock categories used in Fig. 9. This simplified scheme is used in place of the original classifications in order to make clear the general pattern of bedrock distribution in southern Sweden.

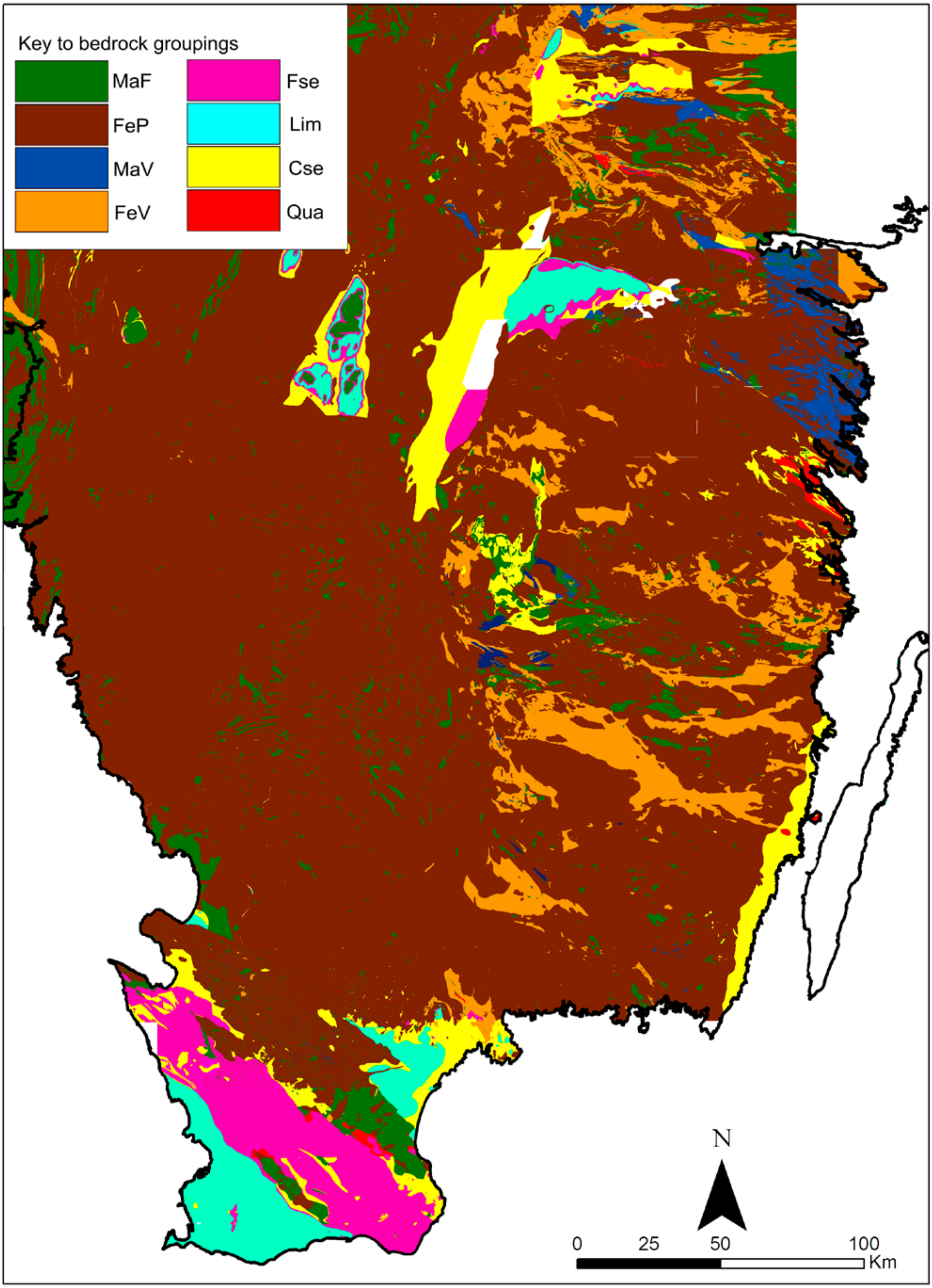

Fig. 9 Generalised overview of southern Swedish bedrock geology. Bedrock geology is generalised to the categories presented in Table 1. Bedrock data is derived from SGU 1:250 000 and 1:500 000 maps.

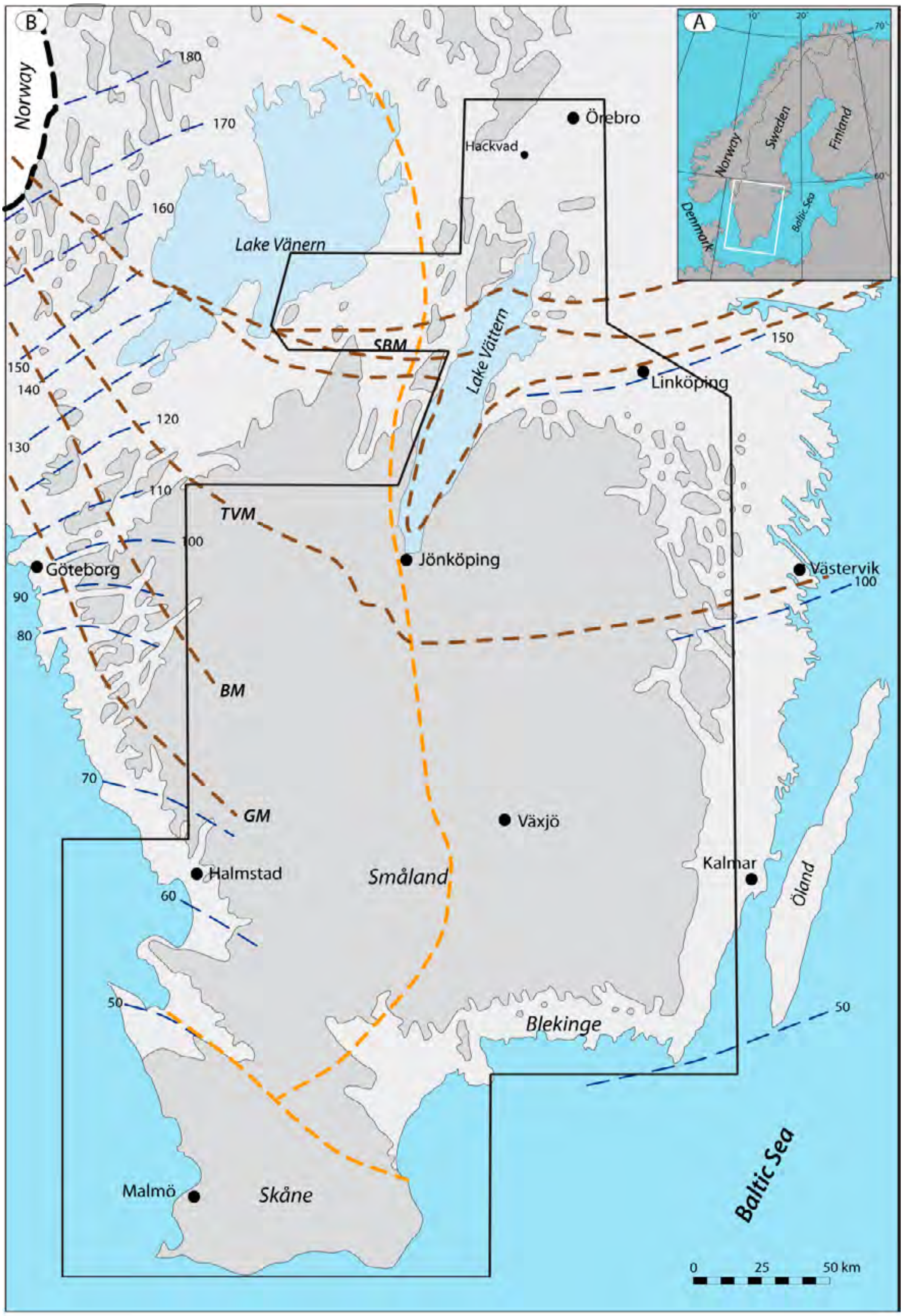

Fig 10. Overview of the southern Swedish study area. (A) Location of study area (white frame). (B) Map of the area. Solid black line demarcates the area in which drumlinoids have been mapped. Areas above the highest shoreline are in dark gray, areas below the highest shoreline in lighter gray, and the regional altitude increase from 50 m asl in the south to 180 m asl in the north, is indicated by blue dashed lines. Brown dashed lines mark major ice-marginal features in south–Sweden; GM = the Göteborg Moraine, BM = the Berghem Moraine, TVM = the Trollhättan-Vimmerby Moraine, SBM = the Skövde-Billingen Moraines of Younger Dryas age. Main bedrock geological zones are demarcated by an orange dashed line (for explanation, see text). All geologic data is taken from Freden (1994).

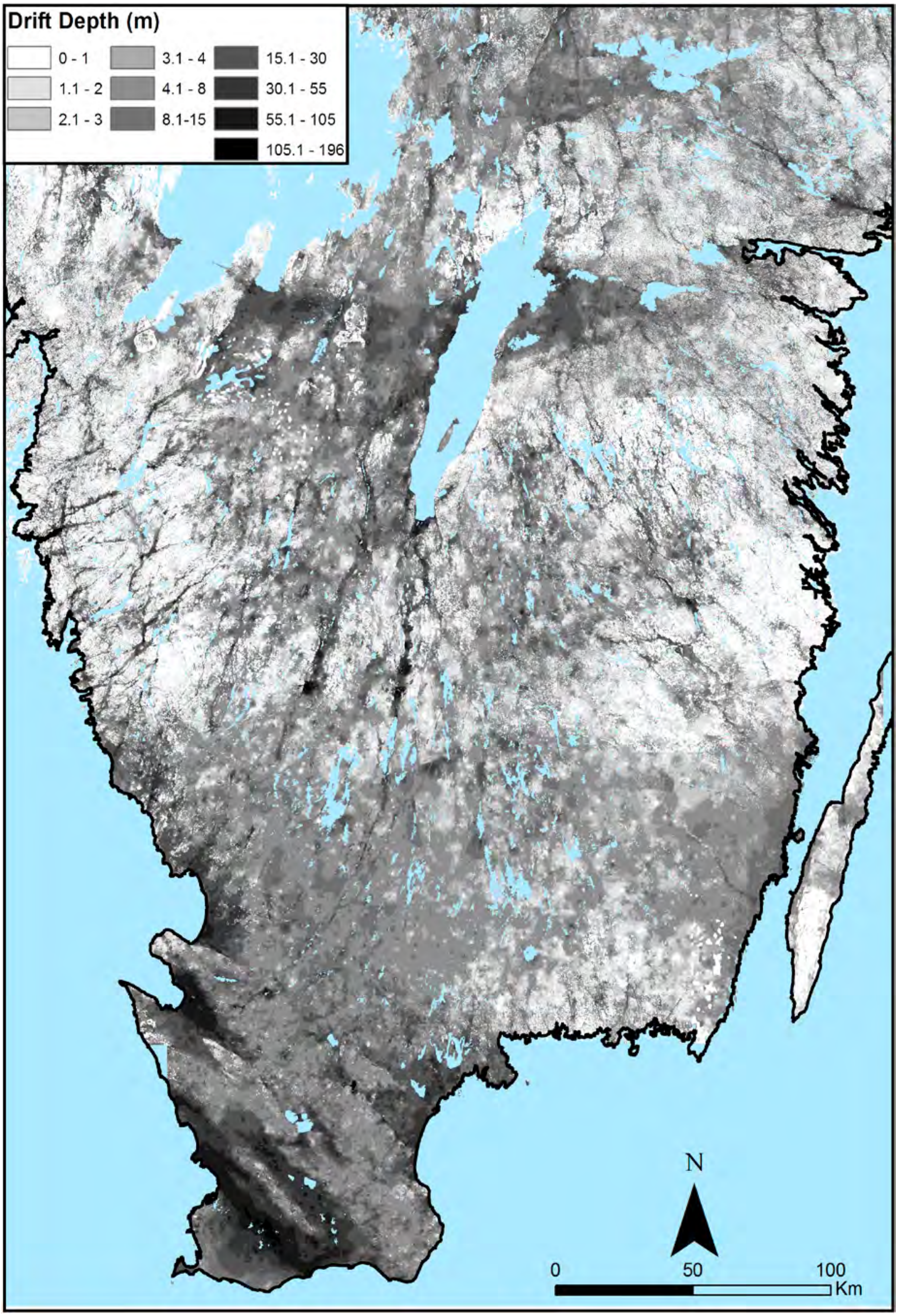

Fig. 11. 10m pixel resolution drift depth (in meters below surface) map of southern Sweden. The data has been presented using a geometric classification due to the log normal distribution of the values. The vast majority of values are in the 0-8 m range and therefore more categories are used here than for the rarer deeper values. Data is from the SGU 10 m pixel resolution drift depth map. Pixels with a 'No data' value are coloured blue, which for the most part indicates lakes and the sea.

are moraine ridge complexes (Fig. 10). Larger features such as marginal moraines, for example the Göteborg and Berghem moraines, and the Younger Dryas-aged Billingen and Skövde moraines (Lundqvist and Wohlfarth, 2001) are visible, as well as smaller features such as De Geer moraines (Lindén and Möller, 2005), which occur in abundance below the highest shoreline in the northern part of the study area. Also revealed to their full extent in the LiDAR DEM is the broad band of hummocky and ribbed moraine stretching from west to east over southern Småland as an, above-the-highest-shoreline, continuation of the Göteborg moraine (Möller, 2010; Möller and Dowling, 2015). Streamlined terrain occurs above as well as below the highest shoreline; thus the subglacial bedform formation is not primarily dependent on the occurrence of proglacial water bodies. However, when occurring below the highest shoreline, the actual morphological height of the bedforms may be masked by an infill of water-lain sediment in the intervening troughs, an effect known as shrouding (Finlayson, 2013).

Materials and Methods

Spatial data

All of the papers presented in this thesis use the light detection and ranging (LiDAR) derived Swedish national height model (SNHM). This height model started to become available to researchers in 2011, with the service fully operable in late 2013. It delivers georeferenced data that has been cleaned and corrected, in a 2 m pixel resolution digital elevation model (DEM) that is of a high quality and covers more than 90% of Sweden at time of writing. The SNHM uses the coordinate system SWEREF TM99 and the vertical reference RH2000. With 0.5-1 points per

Box 2: LiDAR

Light detection and ranging (LIDAR) derived images of the landscape have allowed researchers to both discover new landforms and re-examine the relationships between well-known ones. The unprecedented combination of high horizontal and vertical resolution with wide spatial coverage means that it is perhaps the most ‘true’ image captured of the landscape to date. LiDAR is a type of active remote sensing and operates on the simple principle of firing a beam of coherent light at a surface and measuring the time it takes for the reflected energy/back scatter to return to the emitter (Fig. A)(Rees, 2013). If the position of the emitter/receiver in three dimensional space is also known, then the position of the reflected point can then be calculated. The accuracy of the resulting measurement is dependent on both the characteristics of the target surface and the number of laser points per square meter. Flat, smooth surfaces provide the ‘best’ return whilst steeply angled slopes with lots of vegetation cover or debris provide the ‘worst’ (Hodgson and Bresnahan, 2004).

A key ability of LiDAR is its ability to see through forest cover (Fig. B) to the landscape beneath. This overcomes the limitations of aerial photos which could only visualise the top of the tree canopy and not the surface below it (Frazer et al., 2011). LiDAR beams can penetrate through all but the densest foliage, striking the ground to give points to interpolate from whilst at the same time providing a view of the structure of the canopy from beams that reflect and scatter from the leaves and branches. The vegetation component of the point cloud can then be removed using an algorithm (e.g. Raber et al., 2002).

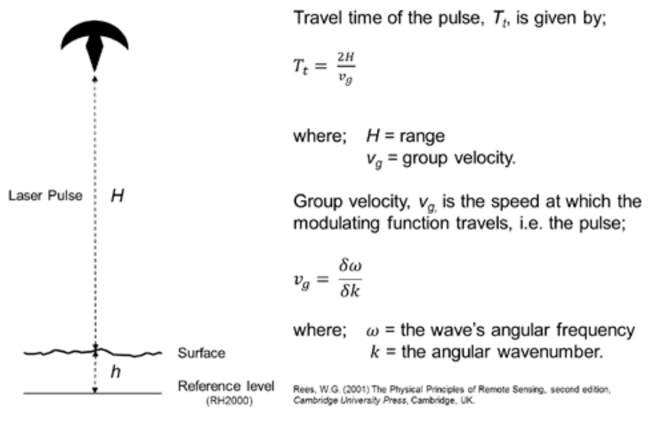

Fig. A. A graphical and mathematical basic summary of how LiDAR works. Equations are taken from the given reference.

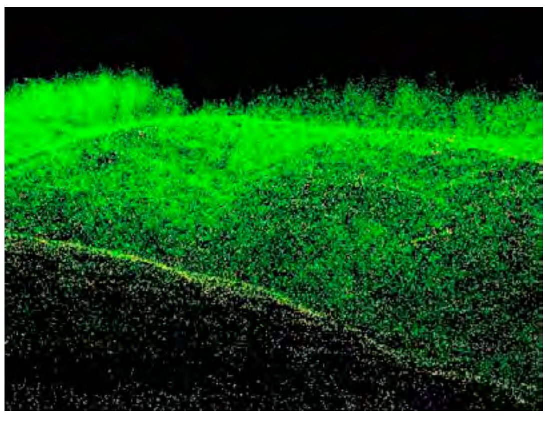

Fig. B. Example of a raw LiDAR point cloud return from a forested area of the Sierra Nevada viewed in three dimensions. Image courtesy of the Kelly Lab, UC Berkeley.

square meter, the average elevation error is better than 0.5 m and the vertical precision is 0.1 m. The data is pre-processed to remove wood cover and urban areas down to 'true' ground level. No further pre- or post-processing of this data was carried out due to the excellent condition in which it is delivered to the end user.

Alongside the SNHM, a range of other spatial data was used in order to try and encapsulate the landscape in which the Swedish drumlinoids are located. These were: (i) bedrock mapping from the Swedish Geological Survey (SGU), (ii) Quaternary unit mapping from the SGU, (iii) the SGU drift depth model and (iv) well log records for the Hackvad area. Again all data is delivered georeferenced to SWEREF TM99; all maps were delivered in polygon format. The bedrock mapping (Fig. 9) used in the self-organising map (SOM) analysis (paper III) is a rasterised composite of 1:250 000 maps where available and 1:500 000 maps to fill the gaps in the higher resolution coverage. The quaternary maps used in the mapping procedure described below is at a scale of 1:50 000. The SGU drift depth model is generated from a combination of well-log data and bedrock outcrop mapping. The accuracy of the model is greatly decreased where there is a lack of well logs to interpolate from. However, in the more densely populated region of southern Sweden this is less of a problem than in the more sparsely populated north. Well logs were also extracted as individual records for the Hackvad area in order to give an idea of the general stratigraphy of the local area prior to excavation and in order to allow the construction of an approximate shrouding effect model (paper VI).

For those regions outside of Sweden the spatial data used is specified in paper III.

Feature mapping

Streamlined features were mapped on hillshade models derived from the SNHM DEM (e.g. Fig. 2). Hillshade models for selected areas were produced with the software package ArcGIS10.0, most often set with an illumination azimuth at 315° and 45°, and all with an angle of illumination set to 20° and a vertical exaggeration of 5. The cell size resolution of the output raster was 2 m; manual mapping was then carried out using the hillshade models as the main visualisation technique. To support the mapping effort in locations that are difficult to interpret, 2-m contour lines generated from the DEM were used in order to help identify breaks in slope. Eskers were mapped at the same time as the drumlinoids; this was done with multi-point lines. Mapping was carried out in two tranches, the first resulted in the dataset presented in Dowling et al. (2015) (paper II) and consists of 10,311 drumlinoids. The second tranche was carried out in order to expand the dataset for paper III and resulted in a final dataset of 23,742 drumlinoids prior to quality control of the extracted bedform parameters (Fig. 12).

Strict criteria must be adhered to whilst mapping the features in order to make the drumlinoid data set as objective as possible and to minimise the influence of user bias (Smith and Clark, 2005; Hillier et al., 2014). The bedform must show a clear preferred orientation of elongation. Secondly, the feature must be upstanding from the landscape in both axes, i.e., a break of slope occurs at the base of the feature that allows for a delineation of its planform shape. We acknowledge that this second criterion does not take into account the potential for the features to be representative of a waveform continuum rather than discrete objects (Clark et al., 2009). Thirdly, we use a low solar azimuth angle (20°) (Smith and Wise, 2007) along with two angles of illumination for comparison purposes at all times. Overall, the landform signal strength is high within the Swedish dataset as the resolution of the LiDAR (2 m) is significantly smaller than modal length and width values of streamlined bedforms from around the world (Hillier et al., 2013) and within Sweden (Hättestrand et al., 1999).

The shrouding effect (Finlayson, 2013) of the true morphological height of the bedforms is caused by water-lain sediments infilling both co- and post-glacial water bodies that inundated southern Sweden up to the highest shoreline, following the subaqueous ice margin recession (see Fig. 10). The result of this can be suites of glacio-marine or glacio-lacustrine silts and clays, and post-glacial lake infill/peat bogs. All of these deposits have the potential to reduce the real depths of the troughs between drumlin ridges and to reduce the horizontal dimensions of the positive features in the streamlined landscape. In areas with a deep drift depth and no outcropping bedrock the shrouding effect could very well mask the relief of the features to a significant degree when considering true height values, thus potentially altering the statistics of this metric by moving the modal values closer to zero.

The second stage in the mapping process was to assign the streamlined feature to one of three categories: (i) soft cored, (ii) rock cored, or (iii) unknown core (c.f. Stokes et al., 2011). Soft and rock cores as defined earlier. An unknown core is one for which there is no direct evidence of internal composition or architecture of the feature. In the case of soft-cored features they have been classified as such when (i) there is a borehole within the feature that indicates a depth of drift greater than the amplitude of the feature, (ii) there is no bedrock outcrop exposed at the surface, either in the LiDAR-derived hillshade models or the geological maps, and (iii) fieldwork confirmed that the borehole records for the area are accurate. A rock-cored feature is mapped as such when bore holes and the geological maps indicate that there is bedrock exposed at the surface in any position along the feature. More often than not this takes the form of a clear crag at the head

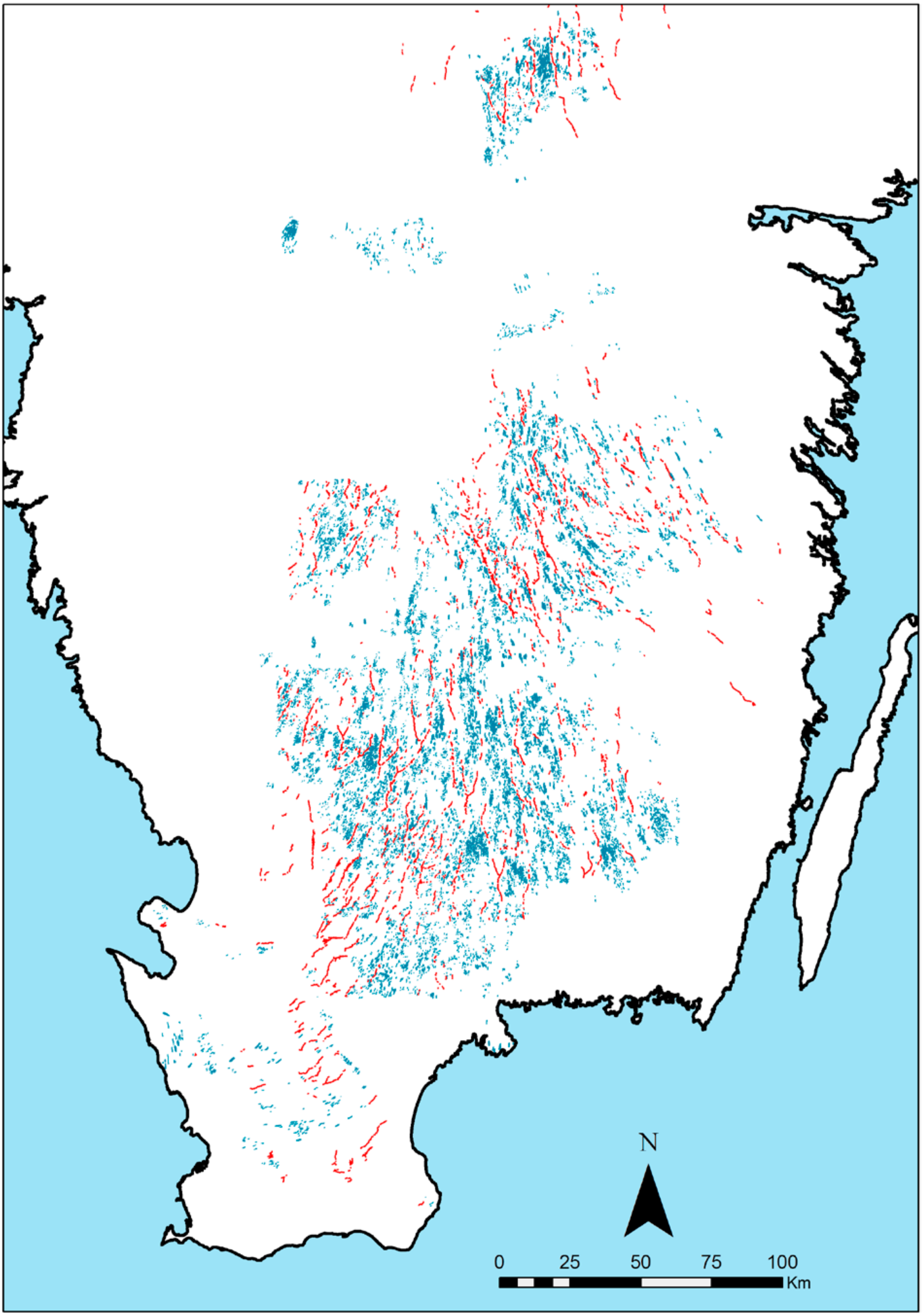

Fig. 12. The mapped drumlinoids of the Swedish dataset; drumlinoids are marked in dark blue and eskers are red lines. Mapping on the eastern half of the country has been carried out completely up to the coast. However on the central-western side of the dataset the mapping was carried out to the border of the extracted SNHM data zones: this is visible in the sharp delineation of the dataset on this flank. This was the result of time constraints.

of a streamlined bedform. However, bedrock exposures can also occur along the length of the bedform. An unknown-cored feature is any feature that does not satisfy any of these criteria, even if in close spatial proximity to features that do. In this way it is possible to gain some appreciation of the distribution of core types seen throughout the data set.

Drumlinoid metric extraction

Length and width extraction was carried out based on the method of Napieralski and Nalepa (2010). Of the various methods that could be used to extract landform height (Hillier and Smith, 2014, and references therein), the basal triangulation approach (Spagnolo et al., 2012) was preferred because of its simplicity. The results were carefully checked against manual measurements yielding a mean difference of ± 12% and a Δh of -0.06 m, which indicates that there is little to no skew of the results introduced by the automated height extraction process. Overall the method produces results with an acceptable potential degree of error across the scale of the features mapped. However, care must be taken to acknowledge the greater potential relative degree of error at sub- 2.0 m height scales as there were problems when a feature had a rough surface (e.g., boulder strewn or degraded by forest removal) and was of very low amplitude (< 1.0 m). This is because at the < 1.0 m scale minor variations around the base of the features will have a greater effect on the interpolation of the basal height and the final height extraction. Therefore all features in the 5th and 95th percentiles were manually cross-checked and removed from the final data set if found to vary from the checked height by more than the average percentage variance of the data set.

Self-organising maps

SOMs are widely used in fields such as finance (e.g. Deboeck and Kohonen, 2013) and are increasingly seen in the natural sciences (e.g. Céréghino et al., 2001; Kalteh et al., 2008). A SOM is a method of exploring and viewing high dimensional data, searching out clusters and visualising similarities, based on the principles of vector quantization (Carnerio et al., 2012). In terms of dimensionality reduction, SOM is similar to a normal principal component analysis (PCA) in that you are taking complex data and attempting to reduce it to the most 'important' variables and relationships in order to explore the internal structure of the data and find those components that best explain its variance (Shaw, 2003). SOMs can also be used to fit functions, carry out prediction and estimation, pattern recognition, noise reduction and classification (Fraser and Dickson, 2007).

A SOM is presented with the raw data and 'trained' in an unsupervised manner; therefore no prior knowledge of the relationships between the data is needed. Training involves comparing the input samples based on variable properties, finding patterns and relationships between samples and variables, eventually learning how these are connected to each other. The strongest connections are preserved and taken forward whilst the weakened ones are discarded.

One of the primary benefits of this method for the data used in this study is that the data can be input as vectors or categorical data. Categorical geological information, such as bedrock type, can therefore be directly compared with continuous variables (vectors) such as drumlinoid length. The SOM achieves this through the sample vector quantization approach. In essence the SOM is making a 2D representation of a complex multi-dimensional data set, whilst preserving the complexity it contains. For an overview of the method as applied to the geosciences, see Fraser and Dickenson (2007).

Field and laboratory work

Fieldwork was carried out over the course of two summers in the area of Hackvad, which is located on the Närke plain (Fig. 10). This area contains soft cored drumlinoids that are situated on a region of relatively deep drift. The internal composition and architecture of two drumlinoids was documented from excavator-dug trenches across most of the geomorphic feature and perpendicular to ridge crests. The section across the large Västergården drumlinoid was 110 m, while at the much more narrow drumlinoid at Hullingsåsen the section was only 25 m across. One trench wall at each site was cleaned by hand scraping and afterwards documented at a scale of 1:20, using standardized lithofacies codes, adapted after Eyles et al. (1983). Fabric analyses in diamict beds were carried out on clasts lying freely in matrix in order to avoid clast direction interference. Clasts were sampled from horizontal benches dug into the diamict over a vertical distance of less than 20 cm. Each analysis comprises 25 or 30 prolate-shaped clasts with longest axis 3-10 cm and a/b-axis ratios ≥1.5. Glaciotectonic structures such as fold axes, fold limbs or overthrusts were measured to their three-dimensional orientation. All orientation data were statistically evaluated according to the eigenvalues method of Mark (1973) and graphically manipulated in Stereonet for Windows. Fabric shape terminology and statistics are according to Woodcock (1977) and Benn (1994).

Grain-size analyses on diamicts, mainly for control of field classification, were carried out by standard methods with wet sieving for extraction of material >0.063 mm, followed by dry sieving of the sand-gravel fractions, and hydrometer analysis for material <0.063 mm. Petrographic analyses under stereo microscope were carried out on gravel grades (2.8-4.0, 4.0-5.6, 5.6-8.0 and 8.0-11.2 mm) at which counted grains per sample varies between 167 and 1005 grains (mean = 570 grains). Determined rock lithology, which was grouped into four categories, (i) crystalline rocks, (ii) sandstone, (iii) clay shale, and (iv) limestone, were checked against reference samples from the Paleozoic stratigraphy of Närke stored at the Department of Geology, Lund University, and/or sampled in the field from bedrock outcrops.

Summary of Papers

Paper I: The new high-resolution LiDAR digital height model ('Ny Nationell Höjdmodell') and its application to Swedish Quaternary geomorphology.

This letter outlines the abilities and potential applications of the Swedish 'Ny Nationell Höjdmodell' (new national height model), as the SNHM was called at the time, with particular reference to the mapping of Quaternary landforms. It highlights the ability of high-resolution, light-detection and ranging data to map terrain in an unprecedented level of detail, even under dense forest cover that has previously hidden key features from view. The primary role of this letter in the thesis is to outline the technical specifications of the SNHM. Since publication a number of the details have changed, for example the means of acquiring the data, however the technical information remains the same. Note that the comment on the curvature analysis has been shown to be incorrect; the errors seen are due to a flaw in the ArcGIS 10.0 toolbox algorithm, not the dataset.

Paper II: Morphometry and core type of streamlined bedforms in southern Sweden from high resolution LiDAR.

This paper generates a new data set of streamlined glacial bedforms in southern Sweden, which is used both to test conclusions from previous work on streamlined bedform morphometrics and to advance our knowledge of streamlined bedforms on the Scandinavian Shield. The data set consists of streamlined glacial bedforms in southeast Sweden mapped from the Swedish National Height Model. 10,311 features were mapped; of the mapped features, 135 are known to have an unconsolidated sediment core, 2120 a bedrock component, and 8055 have an unknown core composition. The extracted morphological variables were then subjected to a univariate and bivariate analysis. We found that the extracted characteristics broadly fit into the lower end of the modal and median value spectrum of similar bedforms from around the world. The distribution of the variables was found to be log-normal to a first-order approximation. The covariant relationships between height and length, width and area were examined after the variables had been log-transformed and were found to be significant, if not particularly strong. Rock-cored features were found to have a longer modal length than soft-cored features, which suggests that reconstructions of past flow velocities from streamlined landforms need to closely consider core-type. Additionally, it was found that there is no support for a derived scaling law for streamlined features by plotting length, width, and elongation ratio against one another.

Paper III: The extent to which geological factors influence the shape of streamlined subglacial bedforms.

This paper uses self-organising maps (SOM) to explore the relationship between streamlined bedform parameters and the geological/geographical environment in which the bedforms are located. The SOM method allows the statistical exploration of data that cannot normally be evaluated by traditional means; categorical data (e.g. bedrock type) can be used in the same analysis as continuous/vector data (e.g. drift depth). Here, three large morphological data sets from Sweden (20 041), Britain (36 104) and Ireland (13 454) are combined with bedrock type, drift depth, basal elevation and distance to esker to see if there are any relationships to be found between them. The results indicate that there are pervasive, very weak to weak, statistically significant correlations between contextual geological/geographical factors and drumlinoid morphology. The most important contextual factor appears to be 'drift depth', followed by 'distance to esker'. Therefore , models of drumlinoid formation. and any efforts to use such features for palaeo-ice reconstruction, must take into account the geological and geographical environment in which they are situated. The logical extension of this is that models of ice-sheet growth and retreat must also take into account and be sensitive to the type of substratum present beneath the ice. Further research into the effect of drift properties on the flow of ice is needed.

Paper IV: The importance of thermal boundary transitions on glacial geomorphology; mapping of ribbed/hummocky moraine and streamlined terrain from LiDAR, over Småland, South Sweden.

In this paper we synthesise previous sedimentological studies and new, high resolution, digital elevation models from southern Småland to investigate the evolution of a deglacial landscape. Starting approximately at the deglacial highest shoreline, there is a 20-40 km wide zone of ribbed and hummocky moraine that can be connected to the predominantly subaqueous Göteborg moraine. North of this there is a dramatic shift into streamlined terrain. Based on sedimentological investigations it was concluded that these zones represent a sub/supraglacial stagnant-ice landsystem, followed by a subglacial active ice landsystem, which during their formations had very different thermal and process regimes along the ice-bed interface (freezing on/frozen versus wet-based basal regimes). New observations derived from high resolution LiDAR digital elevation models reveals patterns of erosional/depositional and morphostratigraphic relationships that have not previously been seen, opening up gateways for future research.

Paper V: Rapid sub-glacial streamlined bedform formation at a calving bay margin.

Using the LiDAR derived Swedish national height model, we have identified previously undescribed shallow streamlined glacial bedforms on the Närke plain of south-central Sweden. These could only be detected with high resolution LiDAR, due to both their subtle size and forest cover. In this area the ice margin receded in a subaqueous environment with a proglacial water depth in the order of 100 m during the last deglaciation. As marked by the configuration of marginally formed De Geer moraine ridges draping the drumlinoids, the receding ice margin formed deeply indented calving bays around subaqueous outlets of the subglacial melt-water drainage, marked geomorphologically to their apex position by beaded esker ridges. The mapped small-scale drumlinoids are aligned perpendicular to the reconstructed ice sheet margin and suggest formation along flow lines adjusted to the configuration of these calving embayments as they propagated up-flow with ice margin retreat. Based on these geometric relationships we argue that the emplacement of drumlinoids was near-marginal, within a maximum distance of ~5 km from the margin, and that they formed on a short timescale (18-30 years).

Paper VI: Streamlined bedforms (drumlinoids) on the Närke plain, south-central Sweden – areal distribution, morphometrics, internal architecture and formation

A flow set of close to 1000 drumlinoids has been mapped by means of LiDAR-derived digital elevation models. The area is situated on the SW part of the Närke plain and its surrounding uplands in south-central Sweden, which was deglaciated in the early Preborial in a glacioaquatic setting. We find that that there is considerable morphologic difference between drumlinoids over crystalline basement areas compared to streamlined terrain over Palaeozoic sedimentary rock basement. The former area is characterized by thin Quaternary drift and the drumlinoids are all of the rock-cored type, built due to active deposition of sediment around obstacles to glacier flow. The latter area is characterized by deep Quaternary drift and the drumlinoids are more elongate and also larger in all dimensions, compared to rock-cored drumlinoids. Irrespective of these geomorphological differences on local landscape scale we find that they remain part of a drumlinoid morphological continuum at the regional scale. Based on the internal sediment architecture as revealed in two cross-drumlinoid sections we find that the soft-cored drumlinoids were formed by compressional constructive deformation, along with excavational deformation along the flanks of the emerging drumlinoids, which shaped the separating troughs. An intermediate-type drumlinoid are those that demonstrate a coupling between underlying Paleozoic sediment strata in areas of shallow drift sheet. These are the result of differing rheological response between incorporated sedimentary rock and a deforming bed below the ice-bed interface. An overall conclusion is

	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Concept and study design	Dowling	Dowling	Dowling	Möller Dowling	Dowling Möller	Möller Dowling
Field work	-	Dowling	-	Möller	-	Möller Dowling
Lab work	-	-	-	-	-	Dowling Möller
ArcGIS	Dowling	Dowling	Dowling	Dowling	Dowling	Dowling
Data sets	Dowling	Dowling	Dowling Hughes Greenwood	Dowling Möller	Dowling	Dowling Möller
Data interpretation /analysis	Dowling	Dowling Spagnolo	Dowling Fraser Åkesson	Möller Dowling	Dowling Möller	Möller Dowling
Writing of manuscript	Dowling	Dowling Spagnolo	Dowling	Möller Dowling	Dowling Möller	Möller Dowling
Comments on manuscript	Möller Alexanderson	Spagnolo Möller	Möller Greenwood Spagnolo Åkesson Clark Hughes	-	Spagnolo	-

Table. 2 Authors' contribution to papers.

that we find geomorphic and architectural compositional differences between the drumlinoids and the flowset they form. We can closely relate these differences to contextual geological differences with respect to basement type and drift depth. We argue that drumlinoid formation is better explained not by one single 'unifying' process but rather a set of processes (erosion/deformation/deposition) by which the subglacial system finds an efficiency equilibrium whereby an obstacle is shaped so that it enhances flow with a minimum of drag, i.e. the typical streamlined form is the result of a positive feedback cycle that tends towards efficiency. This approach argues that equifinality is playing a significant role in drumlinoid formation with a plurality of initial conditions and processes which, when combined with a uniformity of specific overriding processes and mechanical properties, results in a diversity of morphology and core type at the meso-scale and a continuum of landforms at the macro-scale.

Discussion

Solving the drumlin problem?

It was proposed at the end of the introduction that if we combine the ideas outlined by Hart (1997) and Stokes et al. (2013) then we have the majority of the conceptual solution to the traditional 'drumlin problem'. In essence this approach argues that equifinality is playing a significant role in drumlinoid formation and the subsequent differences in formation theory that have arisen. There is a plurality of initial conditions and processes which, when combined with a uniformity of specific overriding processes and mechanical properties, results in a diversity of morphology and core type at the micro scale and a continuum of landforms at the macro scale.

Clark (2010) argues against the widespread use of equifinality in the formation of drumlinoids; whilst he acknowledges that the existence of (in his terminology) clone, emergent and obstacle drumlin types suggest that a measure of equifinality is in place. It is his proposition that a mobile unstable till that becomes wavy is the unifying process in all of these types and therefore there is no true equifinality. However it is suggested here that this is a flawed approach as it fails to acknowledge the potential for processes other than those directly related to the deformation of till to shape drumlinoids. Fluvial erosive processes that act in the troughs could be an example of this as they do not have to be reliant upon a deforming till layer to shape a drumlinoid (Fiore et al. 2002). So, whilst a deforming till layer is almost certainly the key processes in the formation of many a drumlinoid flowset it is not the only possible process. The claim for subglacial deformation to represent a unified model of drumlinoid formation is thus a little premature.

Stokes et al. (2013) take the concept of a deforming till layer as a means of unifying drumlinoid formation theory and apply the instability mechanism to it. By doing this they seek to explain how the four types of drumlinoid core could fit within a unified theory of formation based upon instability propagation. Whilst the arguments presented are persuasive when it comes to deep drift, it remains to be shown why this mechanism needs to be invoked when there is a thin till layer with obvious nucleation points available.

This becomes particularly pertinent when considering the Fennoscandian ice sheet and the bedrock shield on which it was predominantly located in southern Sweden. As illustrated in the regional description, this is an area with a thin till cover (usually <5 m) on shield-rocks (crystalline) with thick till cover rare. In this environment there is little opportunity for the thick, contiguous deforming till layer to form that instability propagation seems to require. Instead sediments are either spread in a thin cover that is 'drumlinised' around bedrock obstacles or are concentrated into smaller areas of deep till patches which are streamlined over their top surface (Fig. 13). With the predominance in southern Sweden of streamlined terrain with exposed bedrock outcrops (see box 3); there is no need for the instability mechanism.

Whilst there was once a deep drift/regolith layer in southern Sweden, this has been removed to the southern margins of the ice-sheet (Kleman et al., 2008). The removal of such regolith is likely to have happened during the repeated glacial cycles of the early to mid-Pleistocene and therefore did not play a role in drumlinoid formation during the LGM (Eyles et al., 1983; Kleman et al., 1997). The lack of further thick drift development is due to the dominance of crystalline bedrock in the shield area tending towards the production of thin tills as opposed to the thicker tills seen preserved in regions dominated by sedimentary bedrock types (Feininger, 1971), e.g. the British vs. Swedish datasets as seen in paper III. Therefore the drumlinised landscape seen today in southern Sweden does not require the instability mechanism to be present in any form, except perhaps in areas of deep till e.g. the Hackvad area (paper VI).

Another 'unifed' theory of drumlinoid formation has recently been proposed by Eyles et al., (in press). The erodent layer hypothesis (ELH) states that drumlinization is a predominantly erosive process that leaves no substantial record in the stratigraphy. Similar to the arguement for efficent modes of flow that is put forward later on in this disucssion, the ELH also argues that a drumlinized landscape is the result of a system that produces a low friction, low slip surface for the rapid flow of ice. Whilst it is entirely probable that the ELH is valid for primarily erosive drumlin fields, there is the issue that erosion has

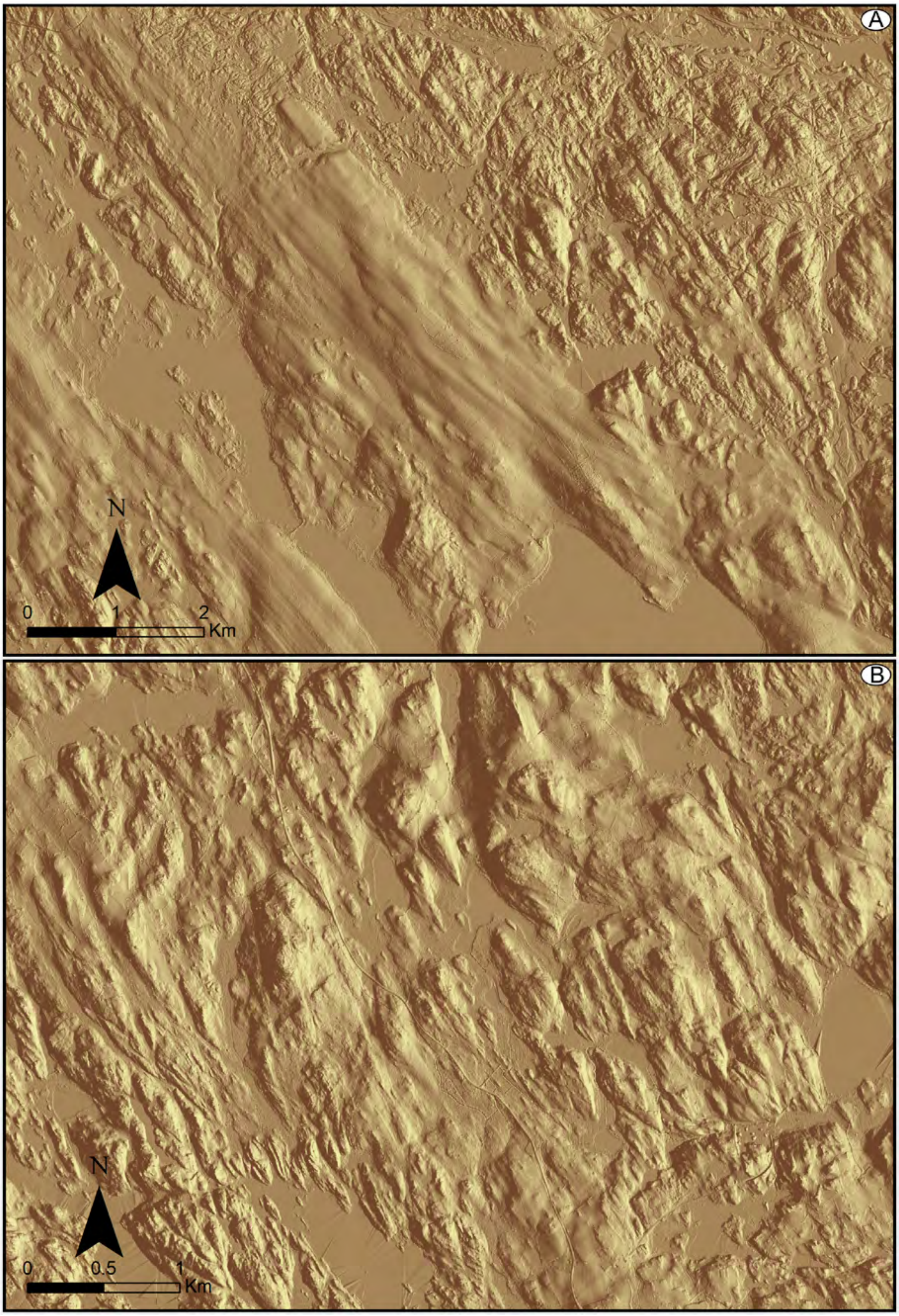

Fig. 13. Example of till patches and obstacle drumlinoids from the Swedish dataset. Panel (A) shows a till patch in the centre of the view with exposed bedrock/minimal till cover to the north and east of it. Note that both the patch as a whole is streamlined and that there are what might be considered individual streamlined hummocks on top of the main patch its self. Panel (B) illustrates an area where bedrock knobs are controlling drumlinoid formation. In both cases the difference in texture between the rough bedrock surfaces and the smooth till is clearly visible in the hillshaded LiDAR data.

been shown not to be dominant/sole process in a number of flowsets from around the world (e.g. Paper VI and discussion therein). This is particularly the case in respect to drumlinoids where deformation has been shown to be playing an important role in, and aligned with, drumlinloid formation. Thus, the ELH does not represent a unified theory of drumlinoid formation as it does not truly account for all streamlined sub-glacial bedforms of core types 2-5.

It is therefore proposed that a conceptual model of drumlinoid formation does not need to rely on one overarching physical process for sediment modification. Instead it needs to consider what processes will predominate considering the local to regional conditions. An example of this the emerging drumlinoid field at Múlajökull (Johnson et al., 2010; Jónsson et al. 2014). Whilst the flowset found at this margin is unlikely to be a good analgoue for ice-sheet scale processes due to surging nature of the glacier. It does demonstrate how an interplay of local factors and fundamental ice properties can combine to produce streamlined subglacial bedforms through a combination of both erosive and constructional processes.

The impact of scale

An interesting aspect of the drumlin problem that has become visible with the advent of large morphological datasets is the importance of relative scale and the potential impact of chaotic behaviour.

Whilst there are many qualitative studies that suggest bedrock is important for drumlinoid formation in terms of both location and size (e.g. Raukas and Tavast, 1994; Rattas and Piotrowski, 2003; Phillips et al., 2010). Greenwood and Clark (2010) quantitatively found that in Ireland factors such as bedrock type and lithological boundaries only seem to have an effect at the local scale and not at the regional. Paper III also finds that bedrock does not have a large measureable influence on drumlinoid shape except in specific local circumstances. In contrast to this the depth of drift is found to have a strong and significant relationship with drumlinoid morphology across the regions studied. This agrees with the conclusion of Greenwood and Clark (2010) that till properties seem to be the most important factor in drumlinoid length, which in turn agrees with the suggestion from the modelling work of Fowler and Chapwanya (2014) that drumlinoid length is most sensitive to till grain size. Overall this suggests that there is a need to consider scale when both conceptually and numerically modelling the formation of drumlinoids as not all variables will have the same behaviour across time and space. The examples given above are related to bedrock type and till properties, but the same probably holds true for the impact of other factors such as hydrological connections and the thermal regime.

The potential of chaos

It has become clear that the majority of factors associated with drumlinoids, be they bedform parameters or contextual variables have log normal distributions when viewed at the regional scale (Dowling et al., 2015). Limpert et al. (2001) highlight how log normal distributions in nature are often the result of a range of variables acting independently of one another in a multiplicative manner. Whilst our variables are likely to be interconnected and

Box 3: rock cores and geo-resistivity

In paper II we state that the majority of drumlinoids in the Swedish dataset are likely to be rock cored. This was based on both the occurrence of mapped bedrock outcrops as outlined in the methods section and previous work of Möller (1987). To test this statement further we recently set up a combined study for probing into the importance of bedrock obstacles to streamlined terrain formation within two small areas in Småland, south Sweden. This was done as bachelors students' projects with aims set out to: (i) carry out a detailed field study of bedrock outcrop occurrence, and (ii) carry out geophysical profiling over two drumlinoids with known rock cores.

Zaman (2015) used LiDAR derived high resolution hillshade models to map out drumlins and possibly occurring rock cores in two test areas. After field check it was concluded that in area (1) 75.9% (n = 114) and in area (2) 92.1% (n = 97) of mapped drumlinoids had visible bedrock components. The method of mapping bedrock outcrops through hill shade models also proved accurate in more than 95% of the cases. This study thus provides strong support for the conclusions drawn in Möller (1987) and Dowling et al. (2015) as to the nature of drumlinoid core types in southern Sweden.

Asani (2015) used resistivity (cves), electromagnetic slingram and induced polarization effect measurements across a drumlin. The study concluded that the drumlin till surface was not controlled by the undulating bedrock underneath and that the distribution of bedrock beneath the drumlinoid does not echo the symmetry of the landform above. This suggests that whilst the bedrock core is locating and initiating drumlinoid formation, it is not directly affecting the surface expression of the resulting landform once till has reached a sufficient depth .

therefore not truly independent, many of these connections are to variables outside of the immediate drumlinoid forming locality, which are in turn linked to even more complex external systems. A simplified example of this is the thermal regime at the base of the glacier. Thermal regimes play an important role in governing the speed of ice flow and the availability of water at the ice-bed interface, both of which are thought to play a role in drumlinoid formation and elongation (Boulton, 1987; Fowler, 2009). The thermal regime at any one given point in time and space is linked to both the overall climate that the ice-sheet is experiencing as well as the pressure induced at the bed by the load of ice above. The ice load in turn has its own series of connections to the climate and flow regimes of the ice sheet, both of which are linked to global patterns of climate change, regional patterns of accumulation/ablation and wind driven snow distribution (Hooke, 2005).

The complexity of this interconnection across space and time leads to factors associated with drumlinoid formation behaving in a semi-independent manner and the production of non-linear relationships. The effect of this is twofold. Firstly, as demonstrated above, overall patterns of response to changes in some contextual variables are applicable at the regional scale whilst others only operate at the local scale. Secondly, it is very difficult to trace backwards from an end state to the initial conditions due to the complexity and depth of potential interactions. This scale dependent variability in response, along with the difficulties in precisely reconstructing how variables have interacted with one another to produce a given end-state, could be indicative behaviour that might described as 'chaotic'. A chaotic system (Katok and Hasselblatt, 2003) is one that has the following properties;

i) *Sensitivity to initial conditions*. Initial conditions are the position of all the variables before the system activates. Sensitivity to these conditions means that each time the initial conditions are changed the resulting output will change also. However the key point in a chaotic system is that the response to this change in conditions is not necessarily linear or monotonic. In the case of drumlinoids an example of this might be the depth of pre-existing drift or the degree of bedrock weathering.

ii) *Subject to topological mixing*. In the mathematical sense 'mixing' can broadly and with a high level of simplification be defined as 'things which are arbitrarily far apart will eventually end up looking nearly the same- if only for a little while' (Chu-Carroll 2010a).

iii) *Has dense periodic orbits*. This can be thought of as meaning that 'things that are arbitrarily close together for long periods of time can have different behaviours' despite their proximity to one another (Chu-Carroll 2010b). Or in geographic terms, things do not necessarily obey the rules of spatial autocorrelation (near things are more like one another than far things).

It is evident that the drumlinoid system is highly sensitive to initial conditions. The range in both morphology and core types seen across previously glaciated regions of the world would strongly suggest that initial conditions are playing an important role in drumlinoid formation. Furthermore it seems that the regional scale continuum and local variability seen in drumlinoid form might satisfy the second condition. And finally, the requirement for dense periodic orbits is perhaps the most interesting one as it means that you cannot distinguish stable orbits/points from unstable ones at any given point in time. Thus not only are the initial conditions sensitive to change in terms of the final outcome, so is the entire system during operation. In the case of drumlinoids we could very simply look at a drumlin field and note that in many cases, despite close spatial proximity, the features vary in size and shape, sometimes by several orders of magnitude. Also of interest in this regard is that small differences in theoretical models of the subglacial environment typically result in big differences in basal temperature and pressure melting point distribution (Hooke, 2005). This could be due to flaws in the model, or perhaps due to a failure to consider the role of chaotic behaviour.

On the other hand it could be argued that the subglacial environment in which drumlinoids form is not a chaotic system but rather a system that we don't yet fully understand and therefore cannot parameterise sufficiently well. Considering that the continuum in morphology is likely to be the result of the properties of over-riding ice, perhaps the most that can be said is that the ice-bed interface and the role of unconsolidated sediments in it are part of a semi-chaotic system.

A general conceptual model of drumlinoid formation

Based on the above discussion and the work carried out for this thesis, the following conceptual model is proposed for drumlinoid formation (Fig. 14). The primary aim of this model is to highlight how processes are related to one another and the multiple ways in which drumlinisation may initiate and proceed.

Overall the flow of time in the model is from top to bottom. However at various points throughout the glacial cycle the formation processes may stop and start again or reset to the start of the model. The four primary stages of the model are:

1) *Initial conditions*: these consist of the geological and geographical variables that are in place before glaciation and drumlinisation occurs. Ice-velocity is included at this stage as well as during the growth phase because a high enough velocity of flow is needed for streamlining

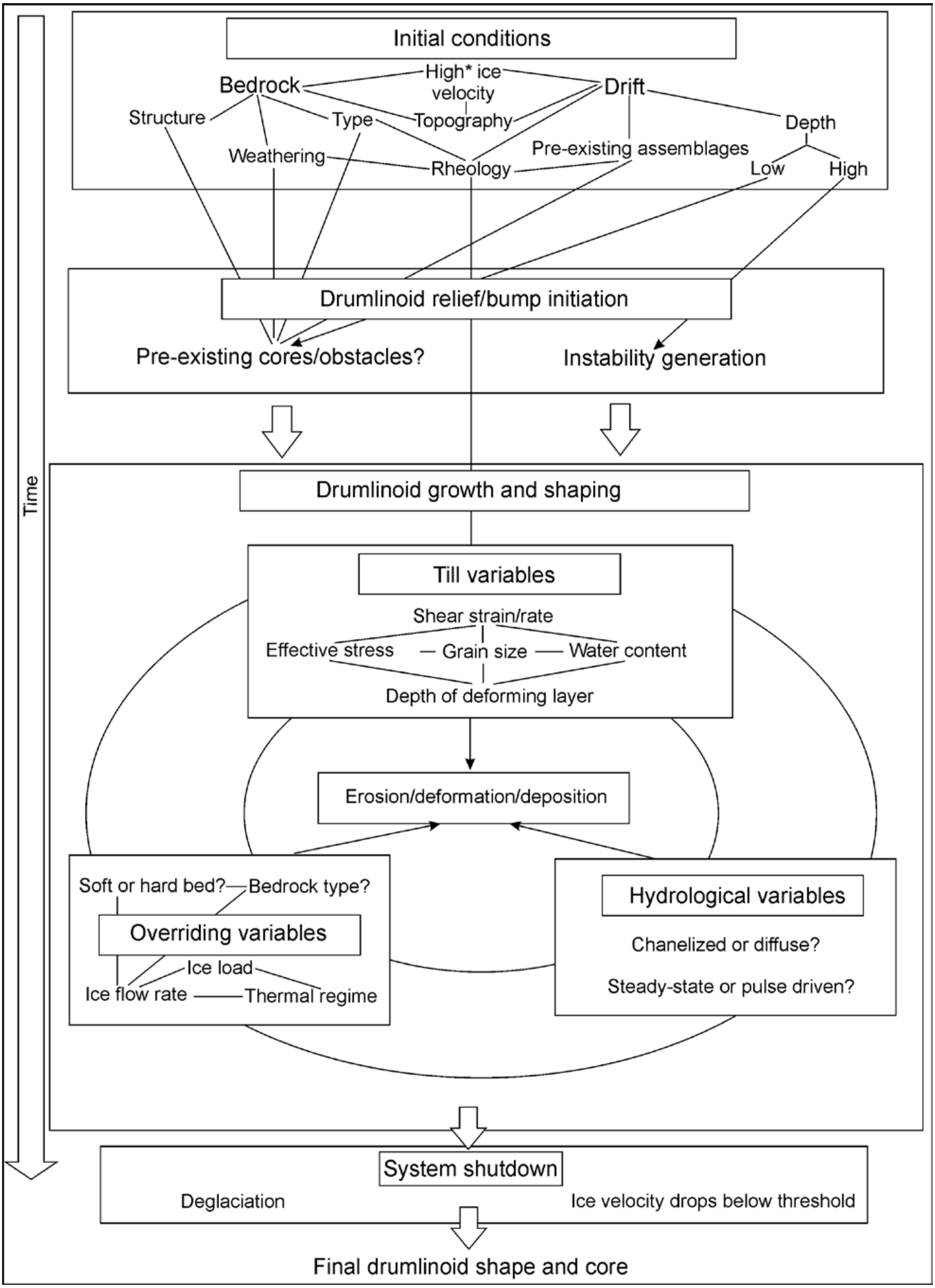

Fig. 14. A generalised conceptual model of drumlinoid formation. Lines ending with an arrow head indicate that either a threshold has been crossed or that a 'decision' has been made. Lines with no arrows indicate that there is a connection in place between the indicated variables. (*) A fast ice velocity is required for streamlining to occur. But how fast is fast? This is taken up in the physical principles of drumlinoid formation discussion.

to commence in the first place. However the velocity may just need to be greater than 0, i.e. not frozen to the bed (see discussion of physical principles). Factors involved in this stage are; existing topographical relief, bedrock variables and drift variables.

2) *Drumlinoid relief/bump initiation*: how does drumlinisation start? In areas of deep homogenous drift then instability generation is likely to be the driver. In regions of shallow drift, spatially limited pre-existing sedimentary assemblages (e.g. outwash fans) and/or bedrock outcropping then obstacle generation is more likely.

3) *Drumlinoid growth and final shaping*: this is the most complex stage and the source of equifinality. The formation of all drumlinoids is subject to the properties of the till/sediments from which they are forming and the interaction of these with the overriding ice, contextual and hydrological variables. The relationships between these three groups of variables are complex and inter-operable. The final landform seen in the drumlinised landscape is the result of the processes that predominate coupled with the amount of time that ice-flow is at a sufficient velocity and sediment flux great enough to effect streamlining.

4) *System shutdown*: streamlining and drumlinoid formation ceases. This may be due to either the complete deglaciation of a given region or due to a change in thermal regime and ice velocity.

This model is an attempt to encapsulate what could be happening at any one point in time for a given local area. The balance between the three groups of drumlinoid growth and shaping variables will shift and change with both time and relative location within the ice sheet. Therefore to predict what type of drumlinoid may arise in a given location the model should be viewed alongside the Stokes et al. (2013) schematic of predicted drumlin occurrence (Fig. 5), which informs both initial conditions and probable mode of drumlinoid initiation. The 'thresholds' that are suggested by the solid arrows in the model indicate where differences in morphology and architecture may arise. This is an attempt to recognise the role probability plays in a given outcome based on the balance of processes acting.

The physical principles of drumlinoid formation

In light of the conceptual model outlined above, how can the physical principles of glacier flow and sediment deformation be related to drumlinoid formation? Many of the variables and factors included in the conceptual model can be broken down and quantitatively defined. Some of the potential interactions that these principles possess as related to drumlinoid formation are highlighted here. Much of the following discussion is based on the glacial mechanic principles as outlined by Hooke (2005). Readers are directed to this work as well as that of Fowler and Chapwanya (2014) for the definition and mathematical parameterisation of the principles in detail. And in the case of the latter reference also for an example of the principles in use with a numerical model.

Why do drumlins form?

As set out in papers V and VI there are three components to the drumlin problem; why, how and where? Smalley et al. (2000) looked at this why question and suggested that the model of a golf-ball and its dimples reducing drag via turbulence was a suitable answer. Clark (2010) highlights that this is not applicable to glaciers as ice flow cannot be turbulent due to its very high viscosity and consequently low Reynolds number. Schoof (2002) looks at the 'why' problem from the perspective of numerically modelling the flow of ice over obstacles and whilst he does not find the 'answer', he suggests that streamlined bedforms greater than ~1 km will act to inhibit ice stream sliding speeds. Taken together these examples suggest that the why question can be answered by examining the relationship between obstacle size and the processes by which glacier ice moves across its bed

The two basic means by which ice movement around an obstacle at the bed occur are regelation and plastic flow. Regelation is the movement of ice around an obstacle by the stoss side melt induced by the increase in pressure and the subsequent refreezing of water on the lee side as pressure drops (Benn and Evans, 2010). Plastic flow (or creep) is the movement of ice around an obstacle due to the deformation imposed upon the ice by the pressure induced by the obstacle (Hooke, 2005). The rate of regelation decreases with the size of an obstacle whilst the rate of plastic flow increases with obstacle size. The resulting total sliding speed is the sum of regelation and plastic flow minus the drag from roughness. These three relationships are summarised in Fig. 15. Examining this relationship it is here posited that the occurrence of drumlinoids and their distinctive morphology is the result of the sub-glacial system tending towards the most efficient obstacle shape and bed for sliding to take place on. The logic for this in the first order is that obstacles enhance sliding speed by increasing melting and plastic flow. However if an obstacle is too 'rough' the increase in basal drag counteracts this. Therefore the sub-glacial system finds an efficiency equilibrium whereby an obstacle is shaped so that it enhances flow with a minimum of drag, i.e. the typical streamlined form is the result of a positive feedback cycle that tends towards efficiency (Hooke and Medford, 2013).

In the second order the concept of a controlling obstacle size is used. This concept (Fig. 15, ℓc) states that there is

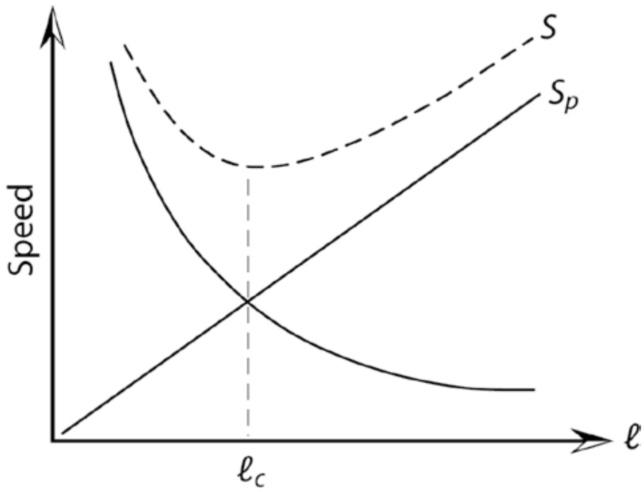

Fig. 15. The relationship between sliding speed and obstacle size for regelation (Sr), plastic flow (Sp) and the resulting sum of the two (S). ℓc marks the proposed controlling obstacle size. Reproduced from Hooke (2005) p.151.

an obstacle size at which neither plastic deformation or regelation are efficient and therefore said obstacles represent the maximum resistance to sliding. This size is proposed to be around 0.5 m (Benn and Evans, 2010. p. 119 and references therein). If the first order argument is correct then an efficiently sliding bed would typically produce landforms that do not fall around this value. The P_{10} and P_{90} values for drumlinoid length, width and height for southern Sweden (paper II) are all significantly above this value and therefore would seem to suggest that this is the case. Smaller features are produced and preserved, but as seen in the percentile values this is a relatively rare occurrence and could be attributed to the semi-chaotic state of the system. The location of these values significantly above the controlling obstacle size might then also be used to suggest that the primary means of ice flow in this region was plastic deformation as opposed to regelation. Additionally the southern Swedish P_{90} length value of 865 m when combined with the Schoof (2002) suggestion of negative effects on speed for features greater than ~1 km might also indicate the upper limit of the proposed efficiency equilibrium.

A weakness of this second order argument is that the horizontal resolution of the LiDAR used to identify the features in the first place is 2 m. Therefore smaller drumlinoids are not as likely to be identified and recorded as larger drumlinoids. However this is somewhat mitigated by the high vertical resolution of the LiDAR that allows the identification of very shallow drumlinoids: the minimum recorded height is 0.3 m.

Where and how do drumlins form?

The Stokes et al. (2013) model of predicted drumlin occurrence (Fig. 5) suggests that the type of drumlin internal architecture seen in any given feature is due to its relative position within the ice sheet and the substrate on which it sits. There are a number of physical principles that support this, particularly in relation to the composition of the till, the role of water, thermal regime and the effect of bedrock. Many of these principles also feed into the question of how a feature forms (Alley et al., 1997). As indicated by Fig. 14 and Fig. 5 (Stokes et al., 2013) the how is dictated by the where, and consequently also the when. The physical processes of drumlinoid formation varying with space and time. Instability theory utilises physical principles to explain how bumps arise and grow on a homogenous surface and many of the same principles can be applied to the growth of bumps around pre-existing obstacles (Boulton, 1987; Hooke and Medford, 2013; Fowler and Chapwanya, 2014).

One of the key elements in the relationship between the spatial distribution of drumlinoids and the processes that create them seems to be the properties of till. Both the work done here and that of Greenwood and Clark (2010) has shown from observations that till depth and properties play an important role in drumlinoid morphology. Theoretical work, for example Schoof (2002) and Hooke (2005), along with the work around instability theory, has also shown that the properties of till are important in controlling rates of ice flow and streamlining behaviour. The first and most obvious statement to make in this regard is that till depth is initially important as some amount of unconsolidated material is needed for deformation to occur and landform growth to initiate. At the other end of the scale deep drift levels may also completely disconnect ice-flow from the properties of the bedrock (e.g. Dowdeswell et al., 2004; Iverson et al., 2003; Roberts and Long, 2005). If this disconnection takes place the properties of the drift and the associated sub-glacial pore water pressure will become the over-riding geological factor in the flow of ice. Therefore the drift characteristics other than depth that are likely to be the most important in regard to drumlinoid formation are particle size (with associated void spacing) and particle lithology. Together these characteristics control the cohesion of the unit as well as the ease with which water and ice can penetrate into the sediments (Boulton and Paul, 1976; Hooke, 2005). The result of this is that fine grained units with higher clay content will be more cohesive and less susceptible to water/ice penetration than coarse grained units with low clay content. Consequently the shear strength and effective pressure experienced by these units should differ, as well as their reaction to changes in water pressure. An example of this at the regional scale is that drumlinoids are more commonly found in regions formerly occupied by ice-sheets than valley glaciers (Menzies, 1979). It is suggested that this is due to the typical composition of the unconsolidated sediments beneath these two different systems. The sediments beneath valley glaciers tend to be coarser than those beneath ice-sheets (Evans, 2003) and therefore are subject to a higher effective pressure when coupled to the hydrological system, thus leading to a lower probability of deformation taking place (Hooke, 2005).

Water plays a key role in the physical processes operating at the base of an ice-sheet and accordingly does so in drumlinoid formation as well. The most fundamental ways in which it does this are: (i) saturating tills and changing their mechanical properties, (ii) enabling the removal of crystalline/strong rocks from the bedrock, and (iii) disconnecting the ice from the bed. A detailed discussion of the mechanics of these processes is not included here; instead it is considered how the variation of hydrological organisation of water across time and space may lead these factors to affect drumlinoid formation.

The organisation of a sub-glacial drainage system can be broadly split into three categories: channelized, diffuse and a linked cavity network. A diffuse state is where a thin film of water is present everywhere at the ice-bed interface. In a channelized system the water is concentrated into either a dendritic or anabranching network. A linked cavity system is where cavities, pockets where ice is not present, under the glacier are held open by high water pressures and linked together by small channels (Benn and Evans, 2010). If a diffuse system is fully in place then the effect is to completely disconnect the ice from its bed and accelerate horizontal velocity. This means that whilst the ice is moving quickly the impact of the acceleration on streamlining would be minimal due to the disconnection with the bed. Drumlinoid construction may thus be inhibited.

A dendritic/anabranching network may have a similar impact as water is drained from the surrounding till, leading to a rigid bed (Clark and Walder, 1994). This is not conducive to drumlinoid formation unless the channelization process occurs patchily and therefore the stiffer sediments provide cores around which deformation of still saturated sediments can take place. However, another possibility is that the evolution and growth of a channelized system can lead to zones of low water pressure, which allows groundwater to upwell from sub-till aquifers and thus create conditions suitable for liquefaction and a more mobile/ductile till layer (Boulton et al., 2007a; Boulton et al., 2007b). This would enable the mobilisation of sediment for drumlinisation, whilst at the same time leaving regions of stiffer sediment for deformation to occur around. The work in paper III is inconclusive in this matter, showing that there may be a relationship between the distance of a drumlinoid from the nearest esker in some glacial settings. But the precise nature of this relationship is difficult to elucidate and impossible to ascribe to any one process or mode of water flow with the data currently available.

Compared to diffuse and channelized drainage organisation, linked cavity networks may well be the most important in terms of drumlinoid formation. This is because not only are these systems more stable than a channelized network and they distribute water more evenly, but they also require high water pressures to remain open (Hooke, 2005). This combination, which creates a patchily deforming bed that also accelerates the flow of the glacier, could create the perfect theoretical conditions for types 2-4 drumlinoid development in a deforming till layer that also incorporates obstacles.

The final role that water could play in drumlinoid development is linked to rapid changes in water pressure. Fluctuations of water pressure in the cavities on the lee side of obstacles provide ice with the ability to remove strong crystalline rock and accelerate the removal of weaker sedimentary rock (Sugden et al., 1992). The more rapid the fluctuations are, the more effective the weakening and removal of the rock is (Hooke, 2005). It is the combination of these pressure variations with the action of rocks embedded in the base of the ice being dragged over obstacles that allows ice to fracture rocks with a greater tensile strength than itself (Hooke, 1991). If these pressure fluctuations are combined with the afore-mentioned linked cavity system on a bed that contains a mixture of bedrock outcrops and unconsolidated sediments, then there is a high probability that drumlinoid formation will occur.

The role of bedrock in drumlinoid formation is suggested to be minimal compared to that of drift properties by work in paper III and others. However, as has cropped up in the above discussion more than once, the type of bedrock on which the physical processes are taking place has an influence. Most likely this is in terms of crystalline rock versus sedimentary rock hardness and relative sediment supply, or due to the nature and chemistry of the particles and solutes delivered to glacial tills and water (Szabo and Angle, 1983). The small but significant correlations seen between some rock types and bedform parameters in paper III could be the fingerprint of this influence. The substantially larger correlations seen between rock type and length in the Irish dataset could also suggest that in the case of the Irish ice sheet glacial factors combined to make the influence of bedrock greater than in Britain or Sweden. However, without a better Irish dataset this is a very speculative conclusion.

And finally we must consider thermal regime. Included as an initial condition for drumlinoid formation, it is postulated that the primary thermal requirement for drumlinoid formation is that the ice is not frozen to its bed and ergo is flowing in some way. This threshold is suggested as Hooke (2005) states that the relationship between thawing and sliding speed is non-linear. 'A bed that is 85% thawed only allows sliding that is 25% of the speed of sliding on a bed that is completely thawed' (Hooke, 2005. p. 194). Logically then the primary thermal boundary condition for streamlining to initiate is a non-frozen bed, followed by a rapid increase in effectiveness as thawing approaches 100%.

Probability

A number of times in this discussion the word 'probability' has been used. The conceptual model of drumlinoid formation presented here is based upon the idea that the final landform seen is the result of different systems combining in different ways to produce the same outcome. This combination of systems can be viewed in terms of probability. Or in other words: how likely is it, given the initial conditions and the combination of processes that then take place, that drumlinisation will occur and what form it will take? This is important as it must be noted that, whilst the drumlinised landscape is very common in formerly glaciated regions, it is not the only type of sub-glacial landscape that we see. As highlighted in paper IV, it can be argued that the position of the thermal boundary will have a significant influence on whether or not a drumlinised or ribbed glacial landscape emerges. In this example it is the state of the thermal regime that is controlling the probability of drumlinisation. In another scenario it might be the depth of drift available or the grain size of the till that makes up that drift. In reality it is likely that all of these variables have threshold values at which the probability of drumlinisation becomes greater than zero, and it is the combination of these probabilities that dictates when drumlinisation occurs.

Conclusions

Whilst the drumlin problem has not been solved here, recent work has started to provide what are perhaps the most important pieces of the puzzle. Recognising that there is more than one way to form a drumlinoid shape is critical to this. After all, the pure rock features that were discarded at the start of this thesis, due to their formation processes being well known, are drumlinoid in shape. The key conclusions of this thesis are:

- Drumlinoids in southern Sweden are predominantly rock cored. Those which do not have a rock core tend to be significantly longer than those that do. In general drumlinoids in southern Sweden are located at the lower end of the size spectrum in terms of global streamlined sub-glacial features.

- Drumlinoids can form rapidly at glacial margins as well as within the main body of ice sheets.

- The most important contextual geological factor in drumlinoid parameter (morphology) formation is drift depth/properties. Bedrock type beneath a feature and the hydrological system as recorded in eskers do play a role, but the exact nature of this is not certain and the correlations are difficult to analyse.

- Drumlinoids may represent the result of a positive feedback system tending towards efficiency of ice flow.

- Whilst it is something of a semantic point, the use of the term drumlinoid is deliberate and important. Due to equifinality there are many landforms that researchers can split into different categories, e.g. rock drumlins, clone drumlins or obstacle drumlins. These are all valid divisions seeing as there are different physical processes involved in their formation. However these processes and the final landforms are all part of the sub-glacial continuum. Hence here they are grouped together and termed drumlinoids, 'drumlin-like', or 'streamlined sub-glacial landforms' to give them their full name.

Research Outlook

Based on the work in this thesis there a number of potentially useful future avenues of research:

(1) *Regional versus local scale*: most of the patterns identified in the contextual variables are from regional scale datasets. It would useful to break down these datasets into discrete flowsets and re-evaluate the results. This would allow for more detail to be included in the bedrock-type data as well as the inclusion of new variables such as local bedrock fracture intensity and till properties other than depth. The flowsets included in this analysis could also be selected based on whether they were thought to be representative of an ice-stream or not, which may allow us to investigate drumlinoid formation in areas of ice-streaming as opposed to areas with slower rates of flow.

(2) *Investigate the role of obstacle size in formation*. This could be done by calculating the size of bedrock component of features and seeing how it relates to properties of the till that makes up the rest of the volume and the total volume/length of the feature. This information would then be useful to models that try to understand the role of controlling obstacle size.

(3) *Further development of instability theory*: whilst it is posited here that instability theory is not a unified theory of drumlinoid formation, it is almost certainly half of the solution, along with core/obstacle based processes and cavity infill. The information provided here on the relative contribution of till depth to drumlinoid morphology may be useful in developing the theory further.

4) *A probability based model of drumlinoid formation*. This could be an interesting path to take for the development of a full conceptual model of formation that is then able to be applied anywhere in the world.

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Svensk sammanfattning

Denna avhandling behandlar strömlinjeformade subglaciala bäddformer (ofta kallade drumliner) i södra Sverige. Det övergripande syftet med denna studie är att bidra till en lösning av det så kallade "drumlinproblemet". Termen drumlin har kommit att tillämpas på en grupp av landformer vars interna sediment, strukturella uppbyggnad och yttre form kan variera kraftigt. Dessa variationer i egenskaper är delvis förklaringen till de olika konkurrerande teorier som lagt fram om drumlinbildning; ofta har varje typ av beskriven intern sammansättning och/eller yttre morfologi genererat nya/andra tankar om hur drumlinbildningen i det speciella fallet gått till. På grund av mångfalden i föreslagna processer föredrar jag att benämna landformsgruppen som drumlinoider ('drumlin-liknande').

I denna studie har ett viktigt hjälpmedel varit den nya svenska nationella höjdmodellen baserad på LiDAR-data från vilken vi kan generera digitala högupplösta digitala höjdmodeller. Detta har kombinerats med detaljerad sedimentologiska undersökningar för att karakterisera strömlinjeformad terräng i södra Sverige och undersöka bildningsprocesser i samband med drumlinoidernas uppbyggnad.

Resultaten av mina undersökningar visar att drumlinoider i södra Sverige är dominant uppbyggda kring en fast bergkärna. Drumlinoider som uppvisar sedimentkärnor tenderar att vara betydligt längre än bergkärnedrumlinoider. I allmänhet ligger drumlinoidformer i södra Sverige i den nedre delen av det storleksspektra som drumlinoider uppvisar inom tidigare nedisade områden i ett globalt kontext. Vidare visar vi att drumlinoider kan bildas under ett kort tidsintevall både i mycket israndnära lägen och längre in under inlandsisen. Den viktigaste kontextuella parametern för drumlinoidbildning verkar vidare vara egenskaperna på och mäktigheten av det underlag i vilka drumlinoidera utformas. Typen av berggrund och det hydrologiska systemet under inlandsisen, som det reflekteras förekomsten av rullstensåsar verkar också spela en viss roll, men den exakta betydelsen av dessa faktorer är inte säker och sambanden är svåra att analysera.

Utöver dessa resultat föreslås en generaliserad konceptuell modell för bildning av drumlinoider kring vilken en diskussion förs om på vilka möjliga sätt olika fysikaliska processer kan påverkar denna bildning. Det föreslås att ett kaotiskt beteende och skalförhållanden ar viktiga parametrar, och även om det kan tyckas i viss mån semantiskt, att det är avsiktligt och viktigt att använda termen drumlinoid för dessa komplexa former. Främsta skälet för det senare är begreppet 'equifinality`, d.v.s. tanken att flera olikartade processer kan leda fram till morfologiskt liknande slutresultat, till exempel att det vi kallar drumlinoider/drumliner har en processmässigt olikartad bakgrund (som bergdrumliner, bergkärnedrumliner eller erosivt bildade drumliner). Dock, även om denna typ av uppdelning är giltig med olika fysikaliska processer involverade i deras bildning så följer de slutliga landformerna ett glacialt form-kontinuum som på överordnad nivå måste betraktas som delar av samma familj.