Program and abstract volume

”The Beauty of Drumlins and the Mystery of their Genesis”,

May 12th 2017

A mini-symposium to honor the retirement of Per Möller

Svante Björck, Per Sandgren
Department of Geology, Lund University

Field work with a ski-doo in Dalarna, central Sweden, February 2001, in search for the oldest possible lake sediments. Photo: S. Björck

On the bridge of Charlie Porter´s ketch Ocean Tramp, December 2005, on our way to carry out multi-disciplinary studies on the island of Isla de Los Estados, Argentina, east of Tierra del Fuego. Photo: S. Björck

In the central Beagle Channel, southernmost Chile, March 2011, in our search for suitable sites for sea level studies. Photo: S. Björck

Professor Per Möller

Per Möller defended his PhD thesis in 1987 after 10 yrs of PhD studies. The reason for that was that much of his time was used up as teacher and administrator, both economically and in terms of teaching. However, large parts of the summers were spent in the field and the outcome was an exceptionally data-rich thesis.

Since then Per mixed his tasks in a similar way, with intense field work and related research-writing, administration, and, very importantly , much teaching. His student excursions became classic: to Blekinge-Småland, Norway and central Sweden. During the latter he showed the beauty of the glacial landscape and its origins but also cooked delicious meals from local food specialties for the students, which was enormously appreciated, especially by foreign students. Per spent his whole career at Lund University in the Department of Geology, where he was one of its key-persons throughout four decades. One of his most challenging and, according to himself, most exciting tasks was to drive the "GeoCentrum project ": the new building of an integrated earth science unit that the Department moved into 2003. And the result was a total reconditioning of the building we meet in today. A great success!!

Career-wise he became a University Lecturer after completing his PhD and in 2006 he was promoted to Professor. He was director of studies for almost 20 years as well as deputy head with economic responsibility for the department. After that he was head of the department for 7 years followed by 5 years as deputy head. Per has also played an important role in the activities of the Royal Fysiographic Society of Lund. After he finished his administrative tasks his research has bloomed further, which can be seen in his publication record.

A very important aspect of Per´s career was that he spent months (adding up to several years!) with field work in Antarctica, Greenland, Russia, Tierra del Fuego and of course Sweden. Per was part of several major international projects (e.g. PONAM, QUEEN and APEX) focused on the glacial history of the Polar and sub-Polar regions, of some called "Möller´s hunting and fishing tours". Here he became well-known for detailed sediment logs in often large sections with the attempt to describe the depositional environment in as detailed manner as possible and place it in a glacial geologic and chronostratigraphic context. Apart from his detailed, even beautiful, logs he was always "generous" in terms of dating control; if possible his sections were bombarded by dates based on different methods, such as ^{14}C, ESR and OSL. Many of his study areas were situated in remote places with difficult logistics, so for example he had to travel months with dinghies along Russian rivers to find the best sections to work with, in contrast to his Swedish field work where he could hire excavators to open up large sections where he wanted them, his so-called "brutal geology". Apart from his exceptional sedimentary logs he was always very interested in and

fascinated by glacial landforms, such as e.g. Rogen moraines, De Geer moraines, ribbed moraines and perhaps especially drumlins, and how they were formed. Although he strongly argued that we need to know what they contain in terms of structures, sedimentology etc, the advent of the eye-opening Lidar technique unfolded many morphological secrets and details, and Per became totally fascinated by this new revolutionizing method. He has always been an advocate for promoting multi-disciplinary studies in order to advance our general understanding. This started already in 1987 with the Björck & Möller Quaternary Research paper on the deglacial environment, attempting to create a more holistic picture of the period of deglaciation in south Sweden. Since then Per has been part of several similar projects/papers trying to tie together different pieces of information to obtain a holistic depiction or model of the development of a region, e.g. eastern Greenland, Tajmyr and Tierra del Fuego. In order to do so one needs to work with other specialists and their techniques. This approach has been demonstrated by Per many times, not least with the multi-disciplinary team in Lund, and during the last few years he has become involved in projects where ancient sedimentary DNA has been used to unravel details in ice age flora and fauna. He is also now part of a large EU project, MicroWine, where DNA plays a key role in identifying microorganisms that are crucial at all stages of the viniculture and vinification processes. Per´s role here is in the group that works with the impact of the soils and their geochemistry. We who know Per feel that he now combines two of his main interests and passions: geology and wine! He will most likely go on with this combination for many years; he actually also plans field work in Tajmyr for 2018. When field work becomes too tough for an oldie he will certainly enjoy one of his many exclusive wine bottles in an arm chair at home. Perhaps even together with one or several of us.

Before this “wine-geology future” will occur we will, however, enjoy two days with Per and drumlins as the main topics. So we want to celebrate Per and give you all the opportunity to meet, have fun and discuss what you probably regard as the most important scientific topic today: the mystery and beauty of drumlins!

In the middle of a jökulhlaup. The evacuation from a gravel bar that was completely flooded in four hours during fieldwork in Johannes V. Jensen Land, Greenland.
Photo: H. Linge 2007

Trapped in the sediment at Beaver Dam during field work in Isla Navarino, Chile.
Photo: P. Sandgren 2014

Mapping glaciotectonic thrust structures in the 1890 moraine complex at Brúarjökull in Iceland.
Photo: Ó. Ingólfsson, 2004

”The Beauty of Drumlins and the Mystery of their Genesis”
PROGRAM MAY 12

Time	Speaker	Affiliation	Title	Page abstract
Session 1, Chairperson Thomas Dowling				
8.45 - 9.00	Svante Björck Per Sandgren	Lund, Sweden	Welcome and introduction	
9.00 - 9.20 *	Anders Schomacker	Tromsø Norway	“The Múlajökull drumlins: stratigraphical and morphological evidence of progressive formation”	6
9.20 - 9.45	Ívar Örn Benediktsson	Reykjavik, Iceland	“Subglacial drumlins at Múlajökull, Iceland”	
9.45 - 10.20	Neal Iverson	Ames, Iowa, US	“A model of drumlin formation based on observations at Múlajökull, Iceland”	8
10.20 -10.50	COFFEE BREAK			
Session 2, Chairperson Sarah Greenwood				
10.50 -11.25	Jane Hart	Southampton, UK	“What evidence do we have for "active" subglacial bedforms forming beneath modern glaciers?”	10
11.25 -11.50	Thomas Dowling	Lund, Sweden	“Geological controls on ice streamlining”	11
11.50 -12.15	John Hillier	Loughborough, UK	“Exploring explanations of subglacial bedform sizes using statistical models”	12
12.15 -13.30	LUNCH			
Session 3, Chairperson Anna Hughes				
13.30 -14.05	Andrew Fowler	Oxford, UK	“The instability theory of drumlin formation”	13
14.05 -14.30	Jan Piotrowski	Aarhus, Denmark	“Ice, water and sediment: conjectures and speculations on the formation of drumlins”	14

* note that a 5 minute discussion after each talk is included

Time	Speaker	Affiliation	Title	Page abstract
14.30 - 14.50	Sarah Greenwood	Stockholm, Sweden	“Drumlin Assemblages and Ice Dynamic Proxies in Marine Environments: Insights from the Gulf of Bothnia”	16
14.50 - 15.25	Mark Johnson	Göteborg, Sweden	“Hummock tracts and drumlins in Småland”	17
15.25- 16.00				
Session 4, Chairperson Ivar Örn Benediktsson				
16.00 - 16.20	Anna L.C. Hughes	Bergen & Bjerknes Norway	37,115 British Drumlins: Insights into Subglacial Bedform Morphometry and Implications for Ice-Flow Interpretations	18
16.20- 16.45	John Shaw	Edmonton, Canada	S-forms: Form, Pattern and Process — Evidence for Megafloods	20
16.45 - 17.10	Kurt Kjær	Copenhagen, Denmark	A 31-kilometre-wide Late Glacial Impact Crater in Northwest Greenland	22
17.10 - 17.35	Per Möller	Lund, Sweden	The Equifinality Issue in Glacial Morphology	23
17.35 - 18.00			Final discussion	
19.00 -	Buffé at the Department for registered participants			

9.00 – 9.20

The Múlajökull Drumlins: Stratigraphical and Morphological Evidence of Progressive Formation

Anders Schomacker[1], Ívar Örn Benediktsson[2], Sverrir A. Jónsson[3], Mark D. Johnson[4], Olafur Ingólfsson[5], Lucas Zoet[6], Neal R. Iverson[7] and Johann Stötter[8]

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Abstract

The drumlin field at Múlajökull, Iceland, is considered to be an active field in that partly and fully ice-covered drumlins are being shaped by the current glacier regime. We test the hypothesis that the drumlins form by a combination of erosion and deposition during successive surge cycles. We mapped and measured 143 drumlins and studied their stratigraphy in four exposures. All exposures reveal several till units where the youngest till commonly truncates older tills on the drumlin flanks and proximal slope. Drumlins inside a 1992 moraine are relatively long and narrow whereas drumlins outside the moraine are wider and shorter. A conceptual model suggests that radial crevasses create spatial heterogeneity in normal stress on the bed so that deposition is favored beneath crevasses and erosion in adjacent areas. Consequently, the crevasse pattern of the glacier controls the location of proto-drumlins. A feedback mechanism leads to continued crevassing and increased sedimentation at the location of the proto-drumlins. The drumlin relief and elongation ratio increases as the glacier erodes the sides and drapes a new till over the landform through successive surges. Our observations of this only known active drumlin field may have implications for the formation and morphological evolution of Pleistocene drumlin fields with similar composition, and our model may be tested on modern drumlins that may become exposed upon future ice retreat.

9.20 – 9.45

Subglacial Drumlins at Múlajökull, Iceland

Ívar Örn Benediktsson[1], Andrew Finlayson[2], Eyjólfur Magnússon[1], Emrys Phillips[2], Luke Zoet[3], Neal Iverson[4] and Jeremy Everest[2]

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Abstract

The Múlajökull drumlin field, Iceland, is the only known active drumlin field and thus provides an excellent opportunity to investigate actively forming drumlins as well as structures in the ice moving over them. The stratigraphy and morphology of the exposed drumlins are described in recent studies and models for their formation and morphological evolution proposed (Johnson et al. 2010; Jónsson et al. 2014; Benediktsson et al. 2016, McCracken et al. 2016). The models suggest that the location of proto-drumlins is determined by initial crevasses in the ice margin and that continued crevassing at these locations leads to drumlin growth and evolution through net deposition on drumlin crests and lee slopes and net erosion on their flanks and proximal slopes. These previous studies also predict that more drumlins exist beneath the present ice. Here we present ground penetrating radar and ice radar data that confirm the existence of more drumlins under the present ice margin, a transverse ridge at the upglacier limit of the drumlin field, and an overdeepening there beyond. The radar data also identify englacial structures that appear to be associated with ice movement over the drumlins. Extension fractures (r-shears) are dominant features on the stoss sides of drumlins and are likely to facilitate ice thinning and enhanced water migration into open fracture networks whereas thrust faults are more prevalent between drumlins, indicating ice convergence, thickening, and compression of drainage pathways. These processes are likely to influence the patterns of effective normal stress and drumlin formation beneath the glacier margin.

References:

Johnson, M.D. et al. 2010. Active drumlin field revealed at the margin of Múlajökull, Iceland: a surge-type glacier. *Geology 38,* 943-946.

Jónsson, S.A. et al. 2014. The drumlin field and the geomorphology of the Múlajökull surge-type glacier, central Iceland. *Geomorphology 207,* 213-220.

Benediktsson, Í.Ö. et al. 2016. Progressive formation of modern drumlins at Múlajökull, Iceland: stratigraphical and morphological evidence. *Boreas 45,* 567-583.

McCracken, R.G. et al. 2016. Origin of the active drumlin field at Múlajökull, Iceland: New insights from till shear and consolidation patterns. *Quaternary Science Reviews 148,* 243-260.

9.45 – 10.20

A Theoretical Model of Drumlin Formation Based on Observations at Múlajökull, Iceland

Neal Iverson[1], Reba McCracken[1], Lucas Zoet [2], Ívar Benediktsson[3], Anders Schomacker[4], Mark Johnson[5], Andrew Finlayson[6], Emrys Phillips[6] and Jeremy Everest[6]

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Abstract

Observations at Múlajökull, a surge-type glacier that has built a drumlin field in its forefield, provide the basis for a theoretical but empirically-grounded model of drumlin formation. Till fabrics based on anisotropy of magnetic susceptibility and clast orientations, along with stratigraphic observations and ground penetrating radar, indicate that drumlin relief results from basal till deposition on drumlins and erosion between them. These data also indicate that surges cause till deposition both on and between drumlins and provide no evidence of the longitudinally compressive or extensional strain in till that might accompany local flux divergence in a deforming bed. Over 2000 measurements of till density, together with consolidation tests on the till, indicate that effective stresses on the bed were higher between drumlins than within them. This observation agrees with evidence that subglacial water drainage during normal flow of the glacier is through channels in low areas between drumlins and that crevasse swarms, which reduce total normal stresses on the bed, are coincident with drumlins.

In the new model, slip of temperate ice across topographic perturbations (sinusoidal undulations) and basal water flow toward bounding channels creates an effective-stress distribution during quiescent flow that maximizes till entrainment in ice on the heads and flanks of drumlins. Crevasses amplify this effect but are not necessary for it. During surges effective stresses are uniformly low, and the bed shears pervasively. Vigorous basal melting during surges releases debris from ice and deposits it on the bed, with deposition augmented by transport in the deforming bed. As surge cycles progress, the net effect of spatially variable erosion between surges and till deposition during them causes undulations to migrate down-glacier and grow increasingly rapidly, owing to positive feedbacks that depend on undulation height. Drumlin growth can be accompanied by either

net aggradation or erosion of the bed, and drumlin heights and stratigraphy generally correspond with observations at Múlajökull. The model, if taken at face value, implies that drumlins formed by non-surge-type glaciers should be dominantly erosional.

Although rudimentary in several ways, this model differs from other theoretical models because it is constrained by field observations at an active drumlin field and contains only parameters that can be measured or estimated independently. The model can also be readily tested because it provides a quantitative prediction of drumlin stratigraphy and defines permissible distributions of effective stress and patterns of till strain, both of which can be inferred from field observations.

10.50 – 11.25

What Evidence Do We Have For “Active" Subglacial Bedforms Forming Beneath Modern Glaciers?

Jane Hart

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Abstract

Over the last 20 years a series of technological developments have allowed us to study subglacial bedforms in new ways. Drumlins are a key part of the deforming bed and an important question is why in some places do we find subglacial bedforms and in others deformation? Hart (1997) showed in a survey of 31 drumlins from all 22 sites worldwide and found the majority are erosional - i.e. they comprise a core and carapace, and the core of the drumlin is unrelated to the drumlinisation.

We report the findings from in situ probes inserted into the till beneath a soft bedded valley glacier Skálafellsjökull, Iceland. This glacier has fluted till and bedrock with crag-and- tails exposed in the foreland. We show the water pressure and tilt over both winter and summer to characterize the nature of the deforming bed beneath this glacier.

We use this to as an analogue to flute formation, and suggest a relationship between flutes and other streamlined bedforms at the site, and relate this to a bedform continuum. We also suggest there are active subglacial ribs (ribbed moraines) beneath the glacier.

11.25 – 11.50

Geological Controls on Ice Streamlining

Thomas Dowling

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Abstract

Ice sheet collapse and the subglacial processes that drive it are a major concern in our warming climate. The subglacial environment is the boundary where the physics of ice flow and the influence of geology meet. Located at this interface are a number critical controls on the speed at which ice sheet flow and subsequent collapse takes place. The now-exposed former beds of past ice sheets, such as the on- and offshore landscape of Scandinavia, provide a powerful means to assess the control that glacial substrates have in governing ice flow behaviour. Former ice behaviour has long been reconstructed from glacial geological evidence from the bed, or modelled based on physical principles of ice flow. Between these two approaches (bed up or ice down) there is a disconnect located at the ice-bed interface. In particular, numerical models (with the power to simulate future scenarios) incorporate ice, climate and ocean laws/forcing, but often treat the bed as passive – it simply exists, rather than interacts. This is partly a problem of process complexity and uncertainty, and partly one of scale: local basal effects have local consequences, but do these translate into regional patterns that influence ice sheet stability and flow as a whole?

This work seeks to examine substrate control on drumlin size and shape in southern Sweden. This is the first deployment of SOM in the glacial field and requires further refinement of the preliminary results in order to better conceptualise the geological landscape. Data collection is complete and the software has been implemented. Initial results indicate that sediment depth is the primary geological driving force behind streamlining behaviour. The primary task remaining is to re-conceptualise the statistical analysis of the geological landscape in which the drumlins sit, focusing on better bedrock conceptualisation in particular. This feeds into further development of the drumlin numerical modelling effort started in Barchyn et al. (2016). This effort has produced the first numerically modelled quantitatively testable link between drumlin length, ice velocity and sediment depth. A link that is now viable to be used in the field-based reconstruction of paleo-ice flow.

Reference:

Barchyn, T.E., Dowling, T.P.F, Stokes, C.R. and Hugenholtz, C.H., 2016. Subglacial bed form morphology controlled by ice speed and sediment thickness. *Geophysical Research Letters, 43-14,* 7572-7580.

11.00 -12.15

Exploring Explanations of Subglacial Bedform Sizes Using Statistical Models

John K. Hillier[1]*, Ioannis A. Kougioumtzoglou[2], Chris R. Stokes[3], Michael J. Smith[4], Chris D. Clark[5] and Matteo S. Spagnolo[6]

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Abstract

Sediments beneath modern ice sheets exert a key control on their flow, but are largely inaccessible except through geophysics or boreholes. In contrast, palaeo-ice sheet beds are accessible, and typically characterised by numerous bedforms. However, the interaction between bedforms and ice flow is poorly constrained and it is not clear how bedform sizes might reflect ice flow conditions. To better understand this link we present a first exploration of a variety of statistical models to explain the size distribution of some common subglacial bedforms (i.e. drumlins, ribbed moraine, MSGL). By considering a range of models, constructed to reflect key aspects of the physical processes, it is possible to infer that the size distributions are most effectively explained when the dynamics of ice-water-sediment interaction associated with bedform growth is fundamentally random. A 'stochastic instability' (SI) model, which integrates random bedform growth and shrinking through time with exponential growth, is preferred and is consistent with other observations of palaeo-bedforms and geophysical surveys of active ice sheets. Furthermore, we give a proof-of-concept demonstration that our statistical approach can bridge the gap between geomorphological observations and physical models, directly linking measurable size-frequency parameters to properties of ice sheet flow (e.g., ice velocity). Moreover, statistically developing existing models as proposed allows quantitative predictions to be made about sizes, making the models testable; a first illustration of this is given for a hypothesised repeat geophysical survey of bedforms under active ice. Thus, we further demonstrate the potential of size-frequency distributions of subglacial bedforms to assist the elucidation of subglacial processes and better constrain ice sheet models.

Reference:

Hillier JK, Kougioumtzoglou IA, Stokes CR, Smith MJ, Clark CD, Spagnolo MS (2016) Exploring Explanations of Subglacial Bedform Sizes Using Statistical Models. *PLoS ONE 11(7): e0159489.* doi:10.1371/journal.pone.0159489

13.30 – 14.05

The Instability Theory of Drumlin Formation

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[1]Mathematical Institute University of Oxford, Oxford England and
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Abstract
We summarise the present form of the instability theory for drumlin formation, which describes the coupled subglacial flow of ice, water and sediment. This model has evolved over the last twenty years, and is now at the point where it can predict instabilities corresponding to ribbed moraine, drumlins and mega-scale glacial lineations (MSGL), but efforts to provide numerical solutions of the model have been limited. The present summary adds some slight nuances to previously published versions of the theory, notably concerning the constitutive description of the subglacial water film and its flow.

A new numerical method is devised to solve the model, and we show that it can be solved for realistic values of most of the parameters, with the exception of that corresponding to the water film thickness. We show that evolved bedforms can be three-dimensional and of the correct sizes, and we explore to some extent the variation of the solutions with the model's parameters.

14.05 – 14.30

Ice, Water and Sediment: Conjectures and Speculations on the Formation of Drumlins

Jan Piotrowski

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Abstract

Ever since the pioneering work of Maxwell Henry Close in 1867, drumlins have attracted researchers more than any other glacial landforms, yet their origin remains contentious. This is both unfortunate and challenging because as long as the formation of drumlins and related streamlined landforms is not fully illuminated, the nature of the subglacial interface and some fundamental issues of ice sheet stability and glacial erosion, transport and deposition will remain unanswered.

Based on my field, experimental and numerical studies I give a personal perspective on the processes likely related to the formation of streamlined bedforms. I selectively pick examples from drumlin fields, mega-scale glacial lineations and glacial flutings in Canada, Denmark, Poland, Estonia, North Sea and Svalbard to speculate about the possible influence of (1) till properties, (2) bedrock permeability, and (3) subglacial meltwater drainage systems on the formation and appearance of the streamlined bedforms. I also demonstrate the wide range of drumlin deposits and discuss the mode of subglacial sediment deformation constrained by numerical and laboratory ring-shear experiments.

The data indicate that the shapes and sizes of some drumlins correlate with till grain-sizes: larger and more oval drumlins seem to consist of a coarser-grained till. In areas of coarser-grained (high hydraulic conductivity) bedrock, drumlins seem to be larger and less elongated, which is related to the till deformability modulated by porewater pressure. Drumlin fields are often dissected by subglacial channels (tunnel valleys) suggesting that efficient meltwater evacuation stabilized till advection and terminated the formation of a drumlin field. Examples of streamlined bedforms consisting entirely of till or entirely of outwash sand (with a range of transitions between these end-members) suggest a conflict between making the sediment and making the landform. In some areas a gradual, steady-state till accretion and deformation contributed to drumlin formation whereas elsewhere meltwater erosion of a pre-existing landscape generated a streamlined landscape. Analogue experiments on till deformation suggest a mosaic of strain patterns whereby in some cases

till fabrics seem to evolve and undergo modification as long as shear stress is applied whereas elsewhere the fabrics attain a stable end shape soon after the deformation commences.

The evident diversity of the processes involved in drumlin production including various combinations of glacial deposition, deformation and erosion suggests that the quest for a unifying theory of streamlined bedforms' formation may be flawed in favour of the equifinality: their similar shapes may be generated by different agents with the only common denominator being the spatial and temporal mosaic of subglacial conditions.

14.30 – 14.50

Drumlin Assemblages and Ice Dynamic Proxies in Marine Environments: Insights from the Gulf of Bothnia

Sarah L. Greenwood[1*], Caroline C. Clason[2], Johan Nyberg[3] and Martin Jakobsson[1]

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Abstract

Subglacial landform assemblages in marine-based ice sheet peripheral environments are typically well-organised in a rather binary manner: ice stream assemblages dominated by highly elongate lineations, funnelled through continental shelf troughs and punctuated by grounding zone wedges; and intervening non-stream zones on topographic banks, largely devoid of bedforms. Classical subglacial bedforms, such as drumlins or ribbed moraine, together with well-developed glaciofluvial landform networks, are typically not components of a marine glacial landform assemblage.

Recent high-resolution multibeam bathymetry data reveal extensive glacial landform assemblages on the Bothnian Sea floor, comprising a rich variety of landform types not typical of peripheral marine-based sectors, yet likely related to the deglaciating marginal zone of the Fennoscandian ice sheet. Two neighbouring yet contrasting sets of bedforms, dominated by drumlins and by mega-scale glacial lineations, respectively, are interpreted to indicate contrasting palaeo-ice flow regimes despite their comparable geological, topographic and terminal setting. Here we use multibeam data and subbottom acoustic stratigraphy to explore, quantify and contrast the relationships between subglacial lineations and the wider landform-sediment assemblages in which they are embedded. We examine the potential roles of the subglacial meltwater system, a basal crevasse system, and sediment distribution and flux, in governing the flow regime and consequent subglacial bedform development.

14.50 – 15.25

Hummock Tracts and Drumlins in Småland

Mark Johnson[1] and Gustaf Peterson [1,2]

[1]University of Gothenburg
[2]Swedish Geological Survey

Abstract
The availability of LiDAR elevation data for Sweden has revealed the geomorphology of Sweden in greater detail than before. In Småland (southern Sweden), mapping of landforms has revealed abundant hummocky topography as well as other glacial landforms (drumlins, end moraines and eskers, for example).

Several different hummock morphologies are evident, and we have made a preliminary classification of these. The hummocks occur not isolated but in fields or groups that we refer to as 'hummock tracts.' The most striking feature of the hummock tracts is that most form as radial swathes that are parallel to the regional ice flow, as indicated by drumlins and striations. These hummocky radial swathes, or 'corridors', occur, in places, as erosional valleys, and we suggest that these are tunnel valleys. Elsewhere, the radial tracts are positive elements on the landscape. The morphometrics of the radial hummock tracts show that they have similar dimensions and spacings, longitudinal profiles and adverse slopes as esker networks, tunnel valleys and glaciofluvial corridors identified elsewhere. We thus offer a working hypothesis that these corridors are connected to similar processes and if so produced by subglacial fluvial action.

Currently, at five localities, machine-dug excavations reveal the internal composition of the hummocks in the radial tracts. At one locality, where an esker can be traced atop hummocks, exposures reveal esker sediment on top of sediment of the hummock. The sediment in this hummock is interpreted as subglacial traction till, suggesting the hummock was formed subglacially. However, hummock genesis inferred from this site is unlikely to explain the formation of the variety of all hummocks in the region, and we suspect that there are a variety of mechanisms, including wastage of dead ice, that can produce hummocks and the tracts and corridors they are found in.

16.00 – 16.20

37,115 British Drumlins: Insights into Subglacial Bedform Morphometry and Implications for Ice-Flow Interpretations

Anna L.C. Hughes[1], Matteo Spagnolo[2], Chris D. Clark[3], Paul Dunlop[4], Jeremy Ely[3], Sarah L. Greenwood[5], Colm J. Jordan[6], Felix Ng[3] and Chris R. Stokes[7].

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Abstract

Subglacial bedforms are a characteristic feature of formerly glaciated landscapes spanning a wide variety of terrains while retaining remarkably similar form. These enigmatic landforms have been studied for more than 100 years intriguing generations of glacial geomorphologists. Yet a fully compelling explanation of their formation remains elusive and subject to passionate debate. A major breakthrough for mapping drumlin distributions systematically across wide areas with high precision has been the now widespread availability and increasing quality of satellite and airborne landscape imagery, and derived products e.g. digital elevation models (DEMs). In the British context, despite a once strong tradition and research interest in glacial geomorphology, by 2004 only a fragment of the total drumlin population had been mapped in detail (Clark et al. 2004). This was resolved by 2010 after systematic interrogation of the NEXTMap Britain DEM (5 m horizontal, <1 m vertical), resulting in the first comprehensive countrywide map of subglacial bedforms (Hughes et al. 2010) and a 7-fold increase in the number of identified British drumlins to 37,115 individuals spanning approximately 15% of the country. In this talk we review the gains made in understanding drumlin size and morphometry and the dynamic flow-pattern history of the last British Ice Sheet based on this dataset. For example, we now know that the average drumlin is 629 m long, 209 m wide, has an elongation ratio of 2.9, is symmetrical in both plan and long-profile (i.e. does not display an exaggerated stoss-lee shape), and (at least in Britain) is probably less than 7 m high (Clark et al. 2009; Spagnolo et al. 2010, 2011, 2012).

References:

Clark, C. D., Evans, D. J., Khatwa, A., Bradwell, T., Jordan, C. J., Marsh, S. H., Mitchell, W. A., and Bateman, M. D. 2004: Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas 33*, 359-375.

Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Spagnolo, M. & Ng, F. S. L. 2009: Size and shape characteristics of drumlins, derived from a large sample, and associated scaling laws. *Quaternary Science Reviews 28*, 677-692.

Hughes, A. L. C., Clark, C. D. & Jordan, C. J. 2010: Subglacial bedforms of the last British Ice Sheet. *Journal of Maps 6*, 543-563.

Spagnolo, M., Clark, C. D., Hughes, A. L. C., Dunlop, P. & Stokes, C. R. 2010: The planar shape of drumlins. *Sedimentary Geology 232*, 119-129.

Spagnolo, M., Clark, C. D., Hughes, A. L. C. & Dunlop, P. 2011: The topography of drumlins; assessing their long profile shape. *Earth Surface Processes and Landforms 36*, 790-804.

Spagnolo, M., Clark, C. D. & Hughes, A. L. C. 2012: Drumlin relief. *Geomorphology 153-154*, 179-191.

16.20 – 16.45

S-forms: Form, Pattern and Process
—
Evidence for Megafloods assembled from Videos by Guy Leduc

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Abstract

A video is presented with the goal of demonstrating the importance of meltwater erosional forms (s-forms) to understanding the paeleohydraulics of ice sheets. In the context of this symposium, the meltwater hypothesis for drumlins requires regional-scale floods and processes capable of producing streamlined forms. S-forms provide the critical evidence supporting these criteria. Prior to the video, "text-book" examples of s-forms and analogs are presented, together with processes of formation, thus, allowing use of s-forms in abduction (inversion) to reconstruct subglacial environments. The video opens with an overview of s-forms eroded into a granite and gneiss plain at French River, Ontario. This overview gives the impression of over-all sculpting, a sense of flow direction, and the absence of crosscutting argues for a single flow. Mapping puts the width(w) of the flow at >100 km. Scans of large areas of the bed reveals characteristic s-forms: sichelwannen, muschellbrüche, spindle flutes, furrows, comma forms and undulating beds, together with ubiquitous patches of spiral cavitation marks. The field examples are commonly irregular, though clearly variants of the "text-book" examples. Animation of the formative flows bring the s-forms to life. Overviews of s-forms reveal characteristic patterns presented in 3-D animation. They point to extensive meltwater flows and promise to guide future modeling. Accommodation of vortices suggest depths ~10m. Boulders up to 1.5 m in diameter deposited in crescentic scours and swales of undulating beds suggest meltwater flow velocities(v) of ~5 m/s. Discharge(Q), where Q=w.d.v, is estimated at ~$5x10^6$ m^3/s, in keeping with hydraulic conditions required by the meltwater hypothesis for drumlins. Areas of high relief carry s-forms indicating immersion and probably pressurized flow. S-forms at Cantley, Quebec, contrast with those at French River, largely comprising obstacle erosional marks caused by differences in hardness of the rocks there—marble with included granite and volcanic xenoliths. Overviews of the Cantley site illustrate rock drumlins with tails extending from individual xenoliths or xenolith clusters. The difference between glacial planing and differential erosion by meltwater scour creating obstacles underlies its distinctive rock forms. Rock drumlins, or rock ridges, resulting from differential erosion, ornamented by hairpin furrows set up by horseshoe vortices, long, straight furrow, and cavettos and

large flutes on vertical surfaces reflect meltwater erosion over a range of scale. Planed xenoliths and strong striation illustrate periods of ice-sheet grounding. Meltwater erosion of the glacier bed would have resulted in clasts projecting like cleats with high contact pressures and probable high ice flow velocities as the ice sheet re-grounded, producing strong striation. However, crosscutting sets of striation indicates minimal erosion by glacial abrasion, probably marking short duration of abrasion events. A high relief, sculptured surface with a meltwater signature, lack of evidence for plucking, and limited erosion by glacial abrasion, point to rock drumlin formation by deep, fast-flowing, subglacial meltwater. A final animation shows the complementary relationship between s-forms and erosional drumlins on regional erosional surfaces.

17.10 – 17.35

The Equifinality Issue in Glacial Morphology

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Abstract
A contemporary trend in glacial geomorphology is the quest for single-process theories explaining the formation of all ribbed moraine and the formation of all drumlins and, in the best of worlds, a unifying theory that explains the formation of both in a single context. This is because they are by many geomorphologist regarded as some kind of end members in a bedform system, e.g. as an analogue to the bed system with flat beds – transverse dunes – longitudinal dunes in a fluvial depositional environment. Examples of such attempts are the introduction of the 'instability theory' to the formation of all streamlined terrain and ribbed moraine or, as an alternative to this, the 'erodent layer hypothesis' for single process driven formation of drumlins. However, based on field geology evidence on internal composition and architecture and the internals relation to the exterior form, i.e. the shape of drumlins or ribbed moraine, many glacial sedimentologists would argue that it is instead different processes in their own or in combination that lead to similar form, i.e. look-alike geomorphologic expression – *equifinality* – in spite of different process background for their formation.

From examples of glaciated terrain in Sweden we can show that landforms that by any geomorphic criteria used by glacial geomorphologists should be classified as ribbed moraine by their exterior form show internal architecture and composition that suggest very different process environments at their formation:
Subglacial folding and/or thrust stacking of sediment into what we term perpendicular-to-ice-flow proto ridges at inframarginal rheologic transitional boundaries between deforming/non-deforming ice-bed interphase, in turn leading to lee-side cavity sediment infill distal to the proto ridge (Niemisel genetic-type ribbed moraine).
Stacked sequences of debris-flow sediments, filling in depressions between ice-cored moraines with controlled distribution in frontally stagnated ice which leaves a landscape of moraine ridges after landscape inversion (precursor ridges). Such pre-LGM formed landscape is remolded at a later ice overriding when protecting cold based regime change to warm-based regime at the ice-bed interphase (Rogen genetic-type ribbed moraine).
Active ice-phase zonation of debris rich ice at marginal transition from warm-based to cold-based conditions. These zones of debris-loaded ice (moraine ridge 'embryos') accrete in proximal direction as the marginal zone stagnates and the debris is eventually passively released as melt-out till (Åsnen genetic-type ribbed moraine).

In conclusion for ribbed moraine formation, we argue that totally different and unrelated processes lead to similar-looking landforms, i.e. equifinality.

From examples of streamlined terrain in Sweden we find that the totally dominating type is rock-cored drumlins, while soft-cored drumlins are much less common. We find that:
Rock-cored drumlins were built from stoss-side plastering of till on bedrock knobs, combined with lee-side cavity infill in distal direction from the same, or possibly due to the capture of deforming bed sediments around an obstacle to flow, i.e. purely depositional-type drumlins.
Internal architecture of soft-core type streamlined terrain suggests that drumlin ridges are due to constructional sediment deformation, while intervening troughs are due to excavational deformation.
In some areas of Sweden we find preserved, more or less large patches of pre-LGM sorted sediment sequences with a streamlined top surface. Internal architecture suggests that these are pure erosional drumlins draped with a thin till carapace and possibly a quite thin deformational zone between undisturbed sediment and the capping till.

We argue in the case of streamlined terrain, which often have considerable morphologic difference between features at local landscape scale whilst still remaining part of the drumlin continuum on regional scale, is a product of different processes or process combinations (erosion/deformation/accumulation) in the subglacial system, tending towards the most efficient obstacle shape and thus bedform for sliding to take place on. Therefore 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.