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Erosional origin of drumlins and megaridges

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ABSTRACT

The erodent layer hypothesis (ELH) proposes that drumlinization leaves no substantial stratigraphic record because it is primarily an erosional process that cuts an unconformity across pre-existing bed materials. Drumlins most commonly have autochthonous cores of antecedent till(s), other stiff and coarse-grained sediment and rock or any combination thereof, and are also found closely juxtaposed with rock drumlins within the same flow sets ('mixed beds'). This is at odds with the suggested growth of drumlins by vertical accretion ('emergence') from deforming subglacial till ('soft beds'). ELH argues that drumlins 'grow down' by erosional carving of pre-existing stiff till, sediment and/or rock by a thin (<1 m) layer of deforming subglacial debris which abrades its substrate. This process is well known to the science of tribology (the study of wearing surfaces) where remnant micro-drumlins, ridges and grooves comparable to drumlins and megaridges are cut by debris ('erodent layers') between surfaces in relative motion. In the subglacial setting the erodent layer comprises deforming diamict containing harder 'erodents' such as boulders, clast-rich zones or frozen rafts. Similar, till-like erodent layers (cataclasites) cut streamlined surfaces below gravity-driven mass flows such as rock avalanches, landslides and slumps, pyroclastic flows and debris flows; streamlined surfaces including drumlin-like 'ellipsoidal bumps' and ridges are also common on the surfaces of faults.

Megadrumlins, drumlins and megaridges comprise an erosional continuum in many flow sets. This records the progressive dissection of large streamlined bedforms to form successively more elongate daughter drumlins and megaridges ('clones') as the bed is lowered to create a low-slip surface that allows fast ice flow and ice streaming. Clones are the 'missing links' in the continuum. ELH predicts preservation within drumlins of antecedent remnant tills and stratigraphies deposited earlier in the glacial cycle under sluggish or steady-state ice flows that were then streamlined by erosion under streaming ice flows. The erodent layer may be preserved as a relatively thin, loosely-consolidated surficial till that drapes the streamlined bedform (the 'upper till', 'cap till', 'till veneer', 'till mantle', 'retreat till', or 'englacial debris' of many previous reports). ELH suggests that there is a fundamental commonality of all forms of erosional wear and streamlining on sliding interfaces from the microscopic scale to the macroscopic scale of ice sheet beds.

1. Introduction

Large tracts of drumlins, together with associated megaridges (mega-scale glacial lineations: MSGL; Clark, 1993), are a striking transcontinental feature of North America, comprising according to some estimates as much as 70% of the total area of Pleistocene ice cover and as much as 40% in Scandinavia (Stokes and Clark, 2002; Clark, 2010; Stokes et al., 2012; Spagnolo et al., 2014; Margold et al., 2015). Glacially-streamlined surfaces occur below modern ice sheets and are seen on deglaciated seafloors (e.g., Ottesen et al., 2005; Ottesen and Dowdeswell, 2006; Graham et al., 2009; King et al., 2009; Bingham et al., 2010; Livingstone et al., 2012; Jamieson et al., 2014); they also survive in the pre-Pleistocene rock record (Savage, 1972; Young et al., 2004).

Despite more than a century of study of subglacially-streamlined bedforms, it is still the case that though their origin 'has been much discussed… there is as yet no generally accepted conclusion and the subject is still under active inquiry. Opinion is chiefly divided between the views (1) that they were accumulated beneath the ice under special conditions and (2) that they were developed by the erosion of earlier aggregations of drift.' This statement was written in 1906 by T.C. Chamberlin and R.D. Salisbury who summarized a then already large literature in their classic textbook Geology (v.3. Earth History, p.60) and this theme is commonly repeated (see Ebers, 1925, 1926; Lundqvist, 1970; Trenhaile, 1971; Muller, 1974; Menzies, 1979, 1987; Aario, 1987; McCabe, 1993; Benn and Evans, 2010; Clark, 2010; Knight, 2010a; Bennett and Glasser, 2014).

Glacially-streamlined terrains dominated by drumlins are now viewed as being related to steady-state, relatively sluggish ice flow velocities whereas associated megascale glacial lineations (megaridges) are considered to be the geomorphic record of accelerating ice and fast-flowing ice streams (Clark, 1994; Bourgeois et al., 2000;

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Dowdeswell and Elverhøi, 2002; Stokes and Clark, 2002, 2003; Winsborrow et al., 2004; Evans et al., 2008, 2012; Stokes and Tarasov, 2010; Margold et al., 2015). Early work considered drumlins and megaridges to be separate bedform types (Clark, 1993) but access to satellite imagery and LiDAR data sets reveals they form a continuum where drumlins become increasingly more elongate downglacier. This is now seen as a result of accelerating ice flow velocities and the onset of streaming (Stokes and Clark, 2002; Briner, 2007; Clark et al., 2009; Clark, 2010; Evans et al., 2014; Spagnolo et al., 2014).

Drumlins have been argued to arise from the deformation and local thickening of 'soft' subglacial till beds to form 'bumps' or proto-drumlins (Stokes et al., 2013a, 2013b). This so-called 'instability' model with its requirement of a soft till bed, is at odds however with many reported observations of megaridges and drumlins that are composed entirely of rock ('hard beds'; see Bradwell et al., 2008; Jezek et al., 2011; Livingstone et al., 2012; Eyles, 2012; Eyles and Doughty, 2016; Krabbendam et al., inpress, and references therein) or which formed in areas where overridden sediments had been 'hardened' by permafrost or were too overconsolidated or coarse-grained to undergo pervasive deformation. Rock drumlins and 'drift' drumlins (sediment) also occur closely juxtaposed within some flow sets implying a common origin (Bourgeois et al., 2000; Eyles and Doughty, 2016). While the instability model recognizes the supplementary role of erosion in the final shaping of bedforms (e.g., Boulton, 1987; Stokes et al., 2011; Stokes et al., 2013b) its fundamental thesis is that drumlins emerge from a till bed by selective in situ thickening of a deforming till layer involving wave-like quasi-periodic instabilities at the ice-bed interface. In spite of the possibility that different processes may lead to similar-looking landforms (i.e., 'equifinality' as suggested for ribbed moraine by Möller, 2006, p. 178), it is important that any formative hypothesis for the origin of drumlins and megaridges is capable of explaining their presence on a wide range of geological substrates typical of continental ice sheets.

1.1. Purpose of this paper

This paper arose out of the common observation that drumlins made entirely of sediment ('drift drumlins'; with or without a rock core) are more often than not closely juxtaposed with drumlins composed entirely of rock (rock drumlins) within the same flow set. Furthermore, many drift drumlins are composed of stiff, pre-existing materials that are truncated by the drumlin form and that are clearly unrelated to the drumlin-forming process.

What follows is an attempt to advance understanding and discussion of the origin(s) of drumlins and megaridges by presenting a simple 'erodent layer hypothesis' (ELH) that re-emphasizes the long-recognized role of erosion in the formation of subglacially-streamlined surfaces regardless of substrate type. The present paper briefly shows the relevance of the applied industrial science of tribology to understanding drumlins and megaridges. Tribology is concerned with wear along the interface of different materials (e.g., the field of 'contact mechanics'; Hutchings, 1992; Davis, 2001; Yan, 2013; Stachowiak and Batchelor, 2014) where streamlined micro-forms are commonly produced that are directly analogous to larger glacial counterparts. This paper also demonstrates that the morphology of subglacially-streamlined beds is widely replicated in the non-glacial geologic realm in the form of shear surfaces eroded at the base of large landslides, slumps, rock avalanches, debris flows, pyroclastic flows, and along large faults (e.g., Byerlee et al., 1978; Draganits et al., 2008; Dakin et al., 2013).

2. Origins of drumlins

The drumlin literature is very large. Clark (2010) very usefully divided drumlins into three types; so-called 'emergent' drumlins argued to form by thickening of a deforming till bed, 'obstacle' drumlins preserved (by deposition or erosion) in the lee of bedrock highs, and 'clones' formed by erosional streamlining and bisection of antecedent sediment. Most attention has been directed to the 'emergent' type resulting from deformation of a soft deforming till bed involving upward growth from initial 'bumps' that are also called 'sticky spots,' 'seeds,' 'patches,' etc., (Smalley and Unwin, 1968; Boulton, 1987; Hindmarsh, 1998a, 1998b, 1999; Tulaczyk, 1999; Piotrowski et al., 2004; Bingham et al., 2010; Hooke and Medford, 2013; Stokes et al., 2013a,b; Trommelen and Ross, 2014). Stokes et al. (2013a) invoke subglacial erosion in their instability model (see their Fig. 4) but only as a secondary process that gives the final shaping to emergent drumlins formed *initially* by wave-like deformation across a soft till bed.

2.1. Excavational deformation and substrate erosion

Fig. 1 depicts much simplified vertical profiles through an ice base where a significant proportion of ice flow is achieved by deformation of a thin (>1 m) layer of debris eroded from the underlying substrate. Much work stresses the importance of subglacial deformation as a means of transporting large volumes of debris downglacier and ultimately depositing till as thickened sheets or large end moraines (e.g., Evans et al., 2006). In this regard, Hart (1997) used the term 'constructional deformation' where a thin subglacially-deforming debris layer is able to progressively build a thickened till deposit by continuous or semi-continuous ('punctuated') incremental deposition (Fig. 1A; e.g., Boyce and Eyles, 2000). In contrast, the present paper emphasizes the hitherto largely-ignored role of the deforming layer as an agent of subglacial erosion ('excavational deformation'; Hart, 1997; Fig. 1B) that is able to shape the underlying non-deforming substrate into streamlined bedforms. Geological work on the cores of drumlins has concluded that many are residual forms carved from pre-existing materials (e.g., Shaler, 1889; Alden, 1905, 1918; Armstrong, 1949; Dean, 1953; Gravenor, 1953, 1957; Jewtuchowicz, 1956; Flint, 1957; Clayton and Moran, 1974; Krüger and Thomsen, 1984; Whittecar and Mickelson, 1977, 1979; Stephan, 1987; Newman and Mickelson, 1994; Colgan and Mickelson, 1997; Möller, 2006; Schomacker et al., 2006; Kerr and Eyles, 2007). In this regard, the presence of intact sedimentary bodies including very stiff, highly overconsolidated tills in the cores of drumlins has been explicitly recognized as a challenge to models that invoke bed deformation and the very rapid growth of drumlins from emerging bumps on unstable soft till (see Spagnolo et al., 2014, p. 1445; Dowling et al., 2015). Subglacial shaping of sediment into drumlins by large subglacial meltwater flows (or filling of cavities) has also been invoked (Hanvey, 1987; Shaw, 2002; McClenagan, 2013, and references therein). This is not the place to discuss the merits of the 'megaflood' model (cf., Ó Cofaigh et al., 2010) but the model has highlighted the role of erosion of pre-existing sediment (and rock; Lesemann and Brennand, 2009) in drumlin formation.

The stratigraphy of drumlin cores commonly indicates that many are essentially streamlined islands of pre-existing, antecedent sediment. Deposition is limited to secondary smearing of a relatively thin till cap over a primary drumlinized core of rock and/or sediment (e.g., Krüger and Thomsen, 1984). Hollingworth (1931); Gravenor (1953, 1957) and Eyles and Doughty (2016) have emphasized the intimate juxtaposition of 'solid' (rock) and 'drift' (sediment) drumlins in the same flow sets suggesting a common erosional origin, and also the difficulty of distinguishing them. A similar conclusion was reached by Jewtuchowicz (1956) in his study of drumlins in Poland as did Stephan (1987, p. 344) who concluded that North German 'drumlins originated during a late phase with erosion after a phase of strong accumulation.' Jauhiainen (1975) recognized that many northern European drumlins are cored by glaciofluvial sediments with only a thin surface till, a finding echoed by Wysota (1994). An erosional origin for both rock and till drumlins had first been suggested by Shaler (1889, p.551) who wrote 'in the Adirondacks, and elsewhere where rocks of uniform hardness exist over considerable fields, we find that glacial action shapes their forms so that at a little distance they are readily mistaken

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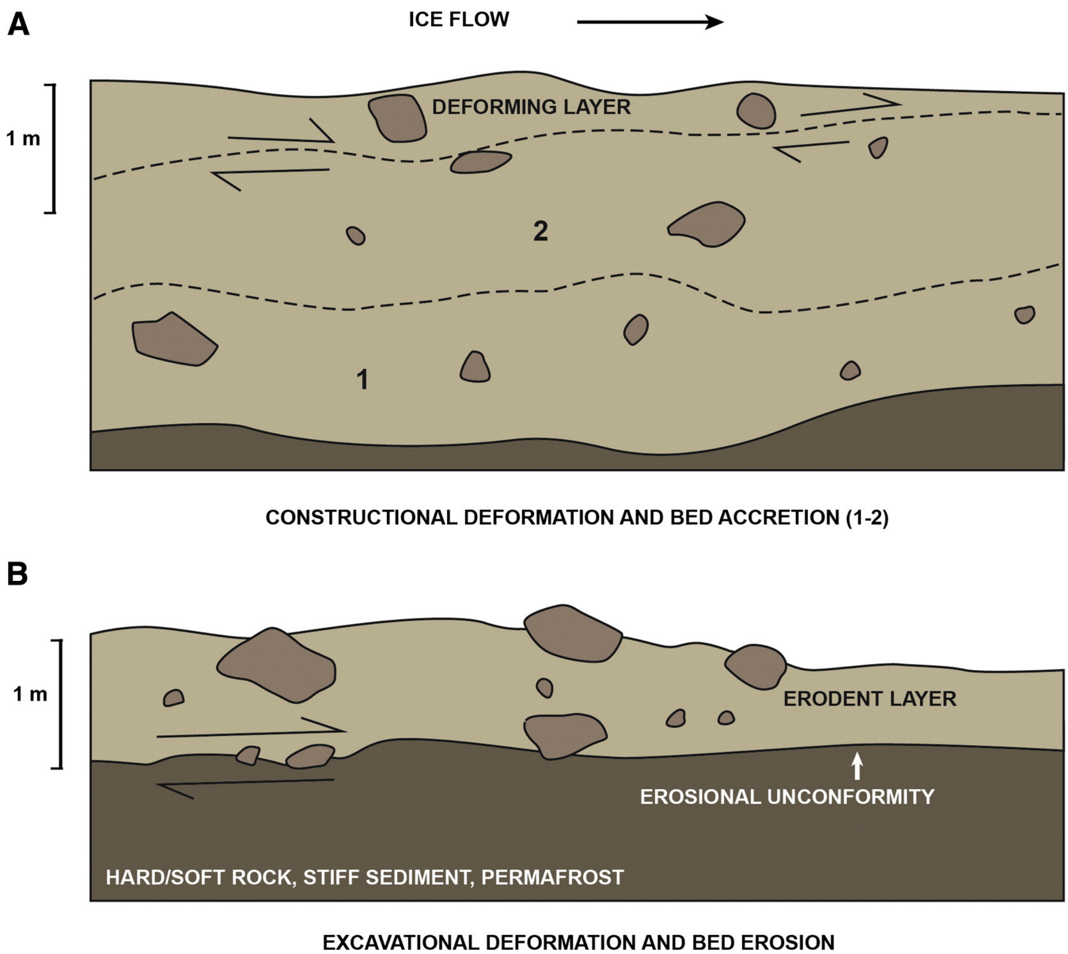

Fig. 1. Contrasting situations where an ice base rests on a thin (<1 m) layer of deformable sediment (after Hart (1997). 'Constructional deformation' (A) results in accretion of a composite till sheet whereas 'excavational deformation' (B) erodes and streamlines the underlying substrate and produces drumlins that 'grow down' into the substrate. These are successively cloned into megaridges under faster flowing ice streams (Figs. 2, 3A, 13).

for drumlins.' Their proximity to sediment-cored ('drift') drumlins implied a common erosional origin. Flint (1957) stressed that the composition of streamlined subglacial landforms ranged 'from 100% bedrock to 100% glacial deposits.' Clayton and Moran (1974, p. 101) argued that drumlins in North Dakota regardless of composition and elongation are the result of erosion of pre-existing sediment 'where glacial sediment of the last advance is so thin that it contributes little or nothing to the volume of the landform.'

The seminal paper of Smalley and Unwin (1968) is the foundation for so-called accretional or depositional models of drumlins but it is important to note that they also (very briefly) presented an erosional model for drumlins involving what can now be called 'excavational deformation,' where 'flowing till flows around it, shaping it so that it causes the minimum disturbance to the flowing stream of till.' Boulton (1987, p. 38) also recognized the possible importance of erosion at the base of mobile, deforming subglacial debris (his 'A' horizon) as it moves across a stiff, non-deforming substrate ('B horizon'). Hill (1971) considered that erosion played a major role in shaping rock and antecedent sediment into drumlins as a consequence of what he termed 'rubbing off.' Boulton (1987) stated that 'erosion will be the most widespread result of extensive deformation of subglacial sediments,' and while he recognized that 'the process clearly has the potential to achieve very high rates of geomorphic work' (p. 32) he did not expand on its fundamental geomorphic role in shaping and streamlining the interface between the deforming layer and its underlying non-deforming substrate, instead focusing on the depositional role of this layer and its glaciological role in allowing ice flow. Clark (2010, p. 1013) noted that deforming till may undergo shear weakening and thinning resulting in its downglacier removal which could aid shaping of a more resistant incipient drumlin highs.

Crozier (1975) used the erosional model of Smalley and Unwin (1968) to explain the intimate association of rock drumlins and drift drumlins across the Peterborough drumlin field of Southern Ontario. He argued that parts of the subglacial till bed could be weakened in response to local increases in porewater pressure that cannot be readily dissipated ('undrained loading') resulting in a decrease in effective pressure. In this process, sediment expands volumetrically by dilation as frictional particle-to-particle contact is reduced and its shear strength, which is dependent on such intergranular contacts, correspondingly declines. Weakened material would be prone to erosion and be selectively advected downglacier leaving residual bed highs on the underlying immobile substrate that could be abraded and streamlined by the abrasive action of mobile debris flowing across its surface. Crozier (1975, p. 184) recognized the presence of older 'compacted drift of a former period of deposition' (i.e., antecedent overconsolidated till) that he argued would be 'prevented from dilating and hence eroding by the overlying ice pressure. Only poorly consolidated material experiences continuous deformation and, in transport past the incipient drumlins, it serves to streamline these areas of higher relief.' The interpretation of drumlins as residual forms shaped by erosive sheets and streams of mobile debris was later employed by Boyce and Eyles (1991) but in hindsight they exaggerated the thickness of the deforming layer.

As related above, Boulton (1987, 1996) emphasized the 'protective' lubricating effects of an overpressured deforming bed arising from its ability to reduce shear stress on the underlying substrate; it is worth emphasizing that this concept was based on observations made below a slowly flowing (<10 m yr^{-1}) ice margin. In contrast, the present paper outlines a hypothesis ('erodent layer hypothesis') for the origin of drumlins and megaridges based fundamentally on the erosive role of deforming subglacial debris under faster flowing ice (Fig. 1B).

3. Erodent layer hypothesis

Deforming subglacial debris that is eroding down into an underlying substrate ('excavational deformation'; Fig. 1B) is defined here as an 'erodent layer.' This layer is created and its thickness (<1 m) maintained ('recharged') by erosion of the underlying stiffer substrate. A subglacial erodent layer containing large clasts, clast clusters and/or a coarse sandy texture has considerable surface roughness both at its base (which allows erosion at its lower bounding surface) and upper subglacial surface (e.g., Tulacyzk, 1999) essential to the coupling of the upper surface to the overlying ice base. Hart (2006) described the abrasional effects of coarse-grained deforming subglacial debris being swept across rock bed of Athabasca Glacier in Alberta, Canada and used the term 'deforming layer erosion' (Fig. 1B). Large boulders and boulder clusters are highly effective erodents ('tools'); by rotating within the erodent layer they promote removal, deformation, scoring and mixing of substrate sediments (e.g., Brown et al., 1987; Fischer and Clarke, 1994; Tulacyzk, 1999; Tulaczyk et al., 2001; Eyles et al., 2015). The same role may be played by other large asperities present in the layer such as 'megaclasts', 'rip ups', 'rafts', 'balls,' 'pods' or 'augens' etc., torn up from the substrate. In analogous fashion, debris flows similarly erode and entrain material (they are said to 'bulk up'; Hungr et al., 2005) derived from an underlying erodible bed (Gray et al., 1999; Egashira et al., 2001; Lê and Pitman, 2009; Hutter and Luca, 2012; Iverson, 2012).

Some models envisage drumlins as having grown upwards from small 'bumps' in a soft till bed arising from systematic quasi-periodic wave-like 'instabilities' at the ice bed interface (Stokes et al., 2013b). ELH suggests instead, that drumlins form by a non-periodic process where they 'grow down' into the substrate as a consequence of the spatial variation in substrate strength and its susceptibility to erosion. The location of any one initial drumlin bedform reflects spatial heterogeneity of the properties (or topography) of pre-existing, antecedent materials overrun by the ice; differential subglacial erosion creates remnant, more resistant 'islands' that can ultimately be shaped and streamlined into drumlins by the action of the erodent layer bypassing the obstacle (Fig. 2). Similarly, any spatial variation in the thickness, velocity and textural heterogeneity of the erodent layer across the ice base will also result in selective erosion of the underlying substrate thereby producing erosional furrows (swales) that isolate larger subglacial islands of sediment or rock. It can be suggested that an undulating subglacial topography of island-like drumlins controls the flow paths of an erodent layer splitting it into narrower fingers of deforming debris (called 'sub-streams' herein) that meander around the base of bed highs resulting in the preferential lowering of swales and the further downwards growth of drumlins. These sub-streams are akin to 'flow bands,' 'fingers' or 'streams' that develop within large, rapidly-moving landslides (Shreve, 1968; Gee et al., 2006; Dufresne and Davies, 2009)

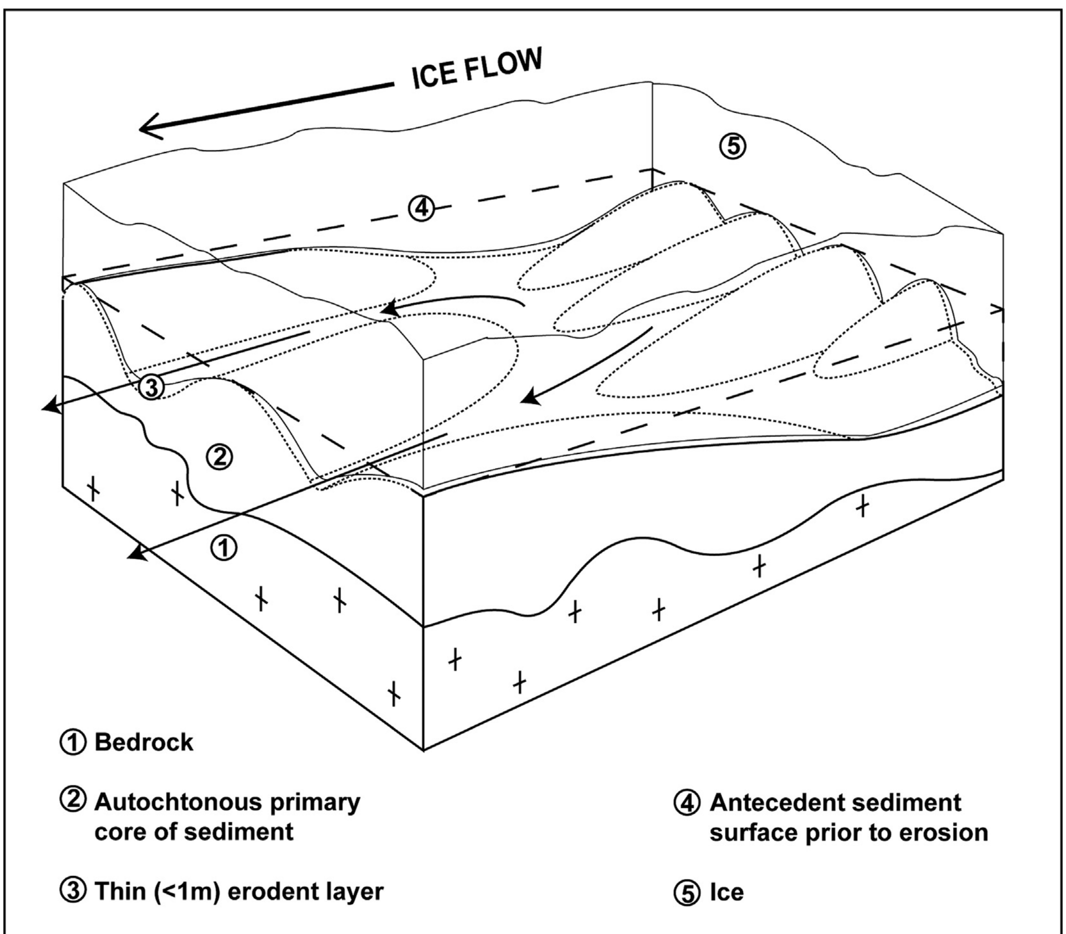

Fig. 2. Simplified model for subglacial streamlined bedforms where a thin erodent layer of deforming debris is swept across the substrate (Fig. 1B). Substrate heterogeneity results in higher-standing remnant 'islands' of antecedent sediments as 'megadrumlins.' These are progressively lowered and dissected by the erodent layer and cloned into drumlins and megaridges with increased ice velocity (Figs. 3A, 13).

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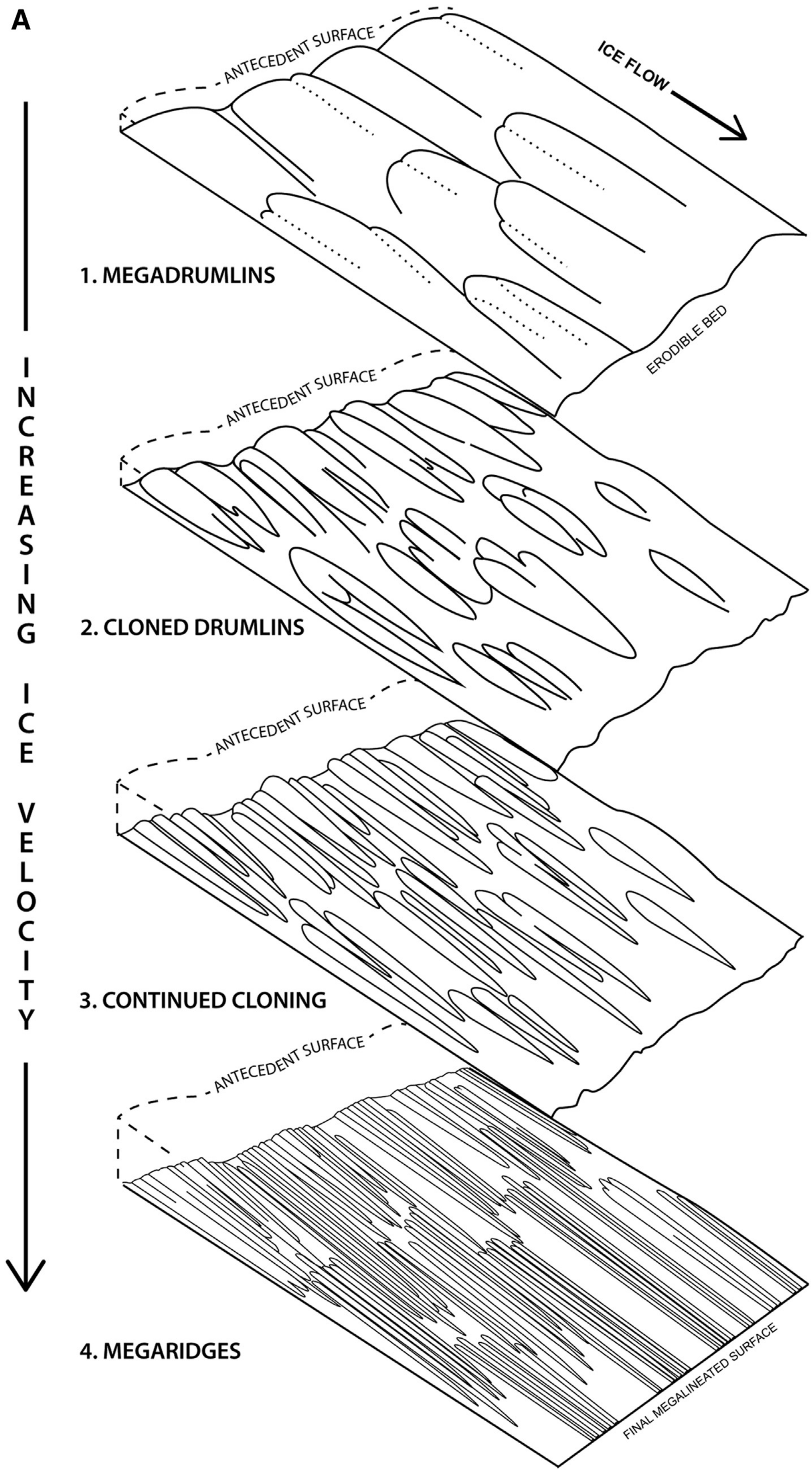

Fig. 3. (A) Erodent layer model where partially streamlined megadrumlins are progressively lowered and dissected into cloned drumlins and megaridges under accelerating ice flow velocities. The process requires an erodible bed of antecedent sediment or rock. (B) Transition from megadrumlins (at left) to drumlins that become increasingly more elongate downstream North East of Galway Bay in Ireland (modified from Clark, 2010). Ice flow from left to right. Note conjoined 'cloned' drumlins resulting from bisection of larger parent drumlins (X) (Fig. 4D) and the presence of barchan-like bedforms (Y) (Figs. 4A, 6, 9).

B

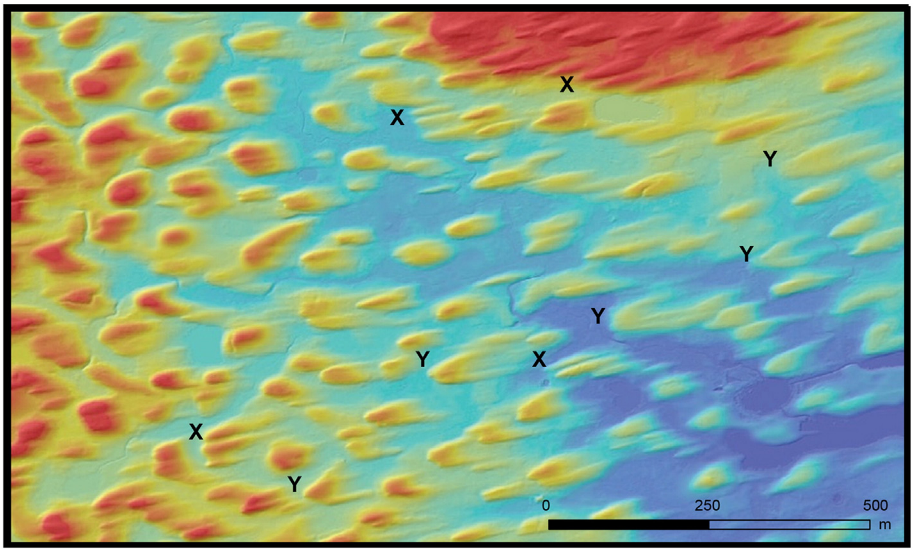

Fig. 3 (*continued*).

which similarly erode into and streamline their substrate (see Discussion below).

Sediments within higher-standing subglacial islands are likely to be relatively well-drained of internal porewaters (and thus stronger) compared to lower-lying more erodible substrate sediments below swales. Similarly, bed highs may shed any excess porewater draining through the erodent layer to perch on less permeable substrate below, especially if the substrate is a relatively stiff, impermeable antecedent till. This will result in a wetter, more mobile erodent layer in swales that is possibly capable of enhanced erosion. In this fashion, the contrast between resistant bed highs and adjacent lows is emphasized by the selective erodibility of weaker, wetter (overpressured) sediments under swales. Swales are essentially meandering 'half-pipes' which act as conduits for the advection of deforming debris downglacier to areas of deposition or moraine construction. Erosion will be promoted in swales and may be more limited across the summits of individual bedforms as is suggested by initial quantitative modeling of the process (Sookhan et al., inpress). In this scenario, one might expect drumlin summits to be largely accordant in elevation reflecting erosion into pre-existing sediment such as outwash.

A final stage of *constructional deformation* and deposition of till is restricted to near the end of the glacial cycle as ice decelerates and the erodent layer velocity also slows. This final depositional phase results in a 'cap till' smeared across the erosional streamlined 'core' ultimately producing the classical smooth 'plastered' surface of the typical drumlin.

ELH further proposes that drumlin fields are restricted to areas where pre-existing sediment bodies such as moraines and broad proglacially-deposited aprons of outwash were overrun by the ice sheet (as noted by Boulton, 1987; Krüger and Thomsen, 1984; Krüger, 1987; Kjaer et al., 2003; Finlayson et al., 2010; Knight, 2010b). In this fashion drumlin fields are examples of what can be called an 'erosional palimpsest landscape.' Some workers, using the assumption that drumlins are the product of extensive bed deformation of relatively 'soft' sediment, have sought an expected relationship between drumlins and the geology of their cores. On the other hand, the results of an ambitious project reported by Greenwood and Clark (2010) noted the absence of any such linkage for >30,000 drumlins in Ireland; indeed, the central premise of ELH is that there is no such relationship because the drumlin form is erosional and truncates underlying materials. ELH does however, predict a very strong relationship between areas of streamlined terrain and the existence of large bodies of thick antecedent sediment (and rock) that could be eroded subglacially into streamlined bedforms. These substrates are likely to be restricted to broad topographic lowlands or offshore basins where terrestrial and shallow marine sediments could accumulate prior to being overrun by ice; such settings also favor the formation of topographically-confined ice streams by funneling ice flow from interior portions of the ice sheet.

The survival of large bodies of antecedent sediment below drumlin fields is expressed geomorphologically as higher-standing 'megadrumlins' (Fig. 3A). Conjoined drumlins occur on their surface suggesting ice flow velocities (or time) were insufficient to allow significant bed lowering and the evolution of free-standing drumlins by continued 'growing down' into the bed. This situation might conceivably develop under sluggish to intermediate (non-streaming) ice flow velocities typical of those areas of the ice sheet lying upglacier of ice streams onset zone, or where ice flow remained in a steady-state mode throughout the glacial cycle. Any increase in ice velocity such as the onset of streaming flow results in a change from a meandering to more straightened flow paths of now much faster-moving debris streams. Faster moving and more erosive debris streams are swept longitudinally over the surface of drumlins and in so doing cut longitudinal grooves (swales) into the parent bedform. In this way, large equant bedforms are subdivided longitudinally into longer, more elongate 'daughter' drumlins (the 'clones' of Clark, 2010) as the antecedent bed is lowered by erosion (Figs. 3B, 4). Continued erosion and dissection of bedforms ultimately produce highly elongated megaridges (megascale glacial lineations; Fig. 5). This is essentially the same process that cuts 'slickenlines' and associated streamlined features on faults as result of poorly-sorted gouge (akin to subglacial debris) being dragged over the underlying fault trace under high confining pressures, and at the base of large landslides (see Discussion below).

ELH proposes that flow sets of megadrumlins, drumlins and megaridges form a well-defined 'erosional landscape continuum' (Figs. 2–4). In effect, it is suggested that an overpressured subglacial erodent layer can be physically modeled as a high-viscosity lubricating layer that is degraded by hard asperities (clast clusters, boulders etc.,) protruding through its base. This layer is very thin relative to ice thickness and can be modeled essentially as a film. At higher high ice velocities (and erodent layer velocities) typical of fast-flowing ice streams (>400 m yr^{-1}) the cloning process, where megaridges are cut from parent drumlins, likely takes place very rapidly within decades as the bed is lowered and eroded debris is quickly advected downglacier (e.g., Smith

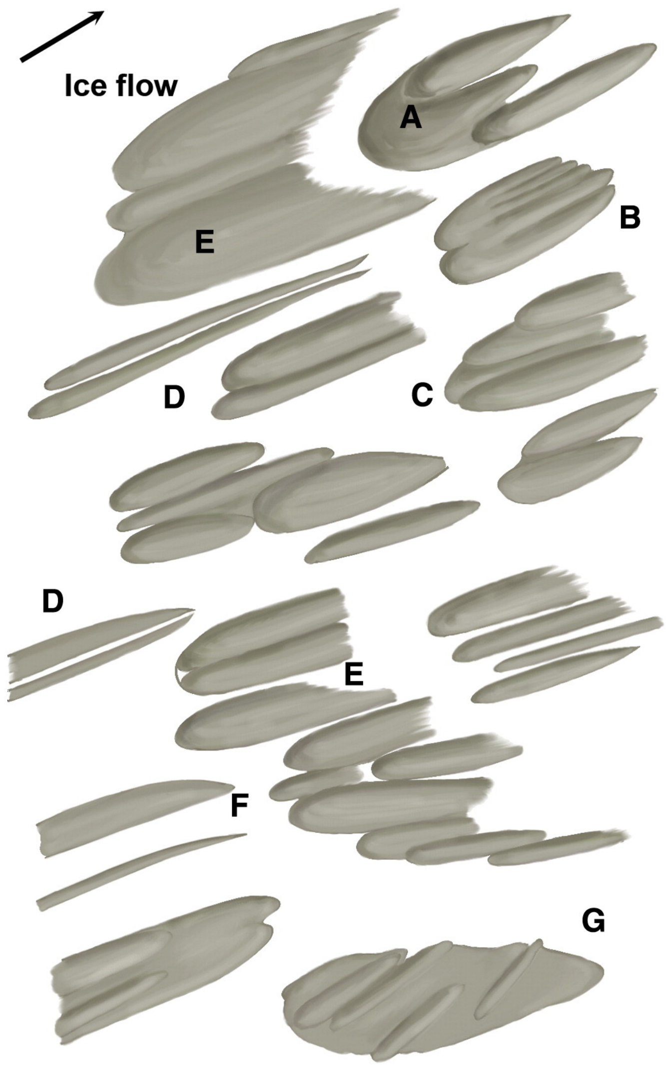

Fig. 4. Provisional classification and terminology of drumlins and clones. (A) Winged, (B) Fingered, (C) Nested, (D) Bisected, (E) Megadrumlin, (F) Asymmetric (half-ellipse), (G) Transverse. Identification of the full range awaits further research using high-resolution imagery such as LiDAR. No scale is implied.

et al., 2007, 2012). Sediment may be selectively stripped off to expose underlying bedrock to the same erosive process (e.g., Hollingworth, 1931; Gravenor, 1953, 1957; Linton, 1962, 1963; Golledge and Stoker, 2006; Eyles, 2012; Eyles and Doughty, 2016) creating drumlinized and lineated 'mixed beds' and 'hard beds' which are much more common across former ice sheet beds than previously thought (see Krabbendam et al., 2016).

A particular type of drumlinized hard bed occurs on sediments in those cases where proglacial deposits were permafrozen, then glaciotectonized under or immediately in front of an advancing ice margin and overrun and drumlinized. It is likely that this sequence of events and process model was very widespread as large ice sheets expanded over surrounding lowlands and one such example is provided by the Burtnieks drumlin field (2000 km^2) of Latvia which occupies a low-lying topographic corridor between 15 and 45 km wide and 80 km long immediately east of the Gulf of Riga (Zelcs and Dreimanis, 1997). Drumlins are carved into glaciotectonized sand, gravels and till, often with large ice-thrust megablock rafts or floes of relatively soft, poorly-cemented Devonian sandstone and shale. A relatively thin till cap on the crests of some drumlins but is discontinuous and commonly absent; where present, it is notably poorly-consolidated in contrast with the highly-consolidated and much thicker tills of the underlying drumlin cores. Large poorly streamlined drumlin uplands (megadrumlins) up to 10 km in length pass downglacier into more streamlined elongate forms where clones and conjoined drumlins are numerous (see Fig. 3B in Zelcs and Dreimanis, 1997). The stratigraphy of these drumlins supports the model of Zelcs and Dreimanis (1997, p. 75) where drumlins were carved by 'vigorous glacial erosion' of hardened glaciotectonized permafrozen strata. This is the expected sequence of events as slowly-moving ice expands across frozen or partially-frozen sediments that undergo sub-marginal glaciotectonism and thrusting and which are then shaped by erosion under faster flowing ice and its thawed erodent layer. Glaciotectonism may create the initial subglacial relief of thrusted highs and lows that can then be shaped into drumlins by abrasive subglacial debris.

Rogen moraines are commonly found on the upstream margin of drumlin fields and are widely attributed to some form of 'thrust and stack' subglacial deformation of a frozen substrate (Dunlop and Clark, 2006; Möller, 2006, and references therein). Their form closely resembles the type of surface damage that occurs to mated metal surfaces in slow relative motion with each other under high confining pressures. Large flakes are sheared off from one metal surface, moved a very short distance and then stick to the surface as a protruding bump (a process called 'macroscopic wear transfer' or 'scuffing'; see Davis, 2001; Kleis and Kulu, 2008; Kovalchenko et al., 2011; Basavaraju and Ranganatha, 2013). The very close morphological resemblance of the distinctive 'fish-scale' morphology of Rogen moraines to displaced 'platelets' adhering to scuffed metal surfaces is noteworthy. Möller (2006) describe examples of Swedish drumlins produced by the erosional streamlining of former Rogen moraines being swept by a layer of mobile subglacial debris. The broader significance of this work is that it suggests that the presence of glaciotectonically-deformed sediment and rock in many drumlin cores (commonly held to be the result of a thick deforming bed during drumlin formation and used to support a genetic link between bed deformation and drumlin growth) may more likely reflect initial glaciotectonism in near ice-marginal settings prior to later drumlinization of the glaciotectonized substrate by an erodent layer.

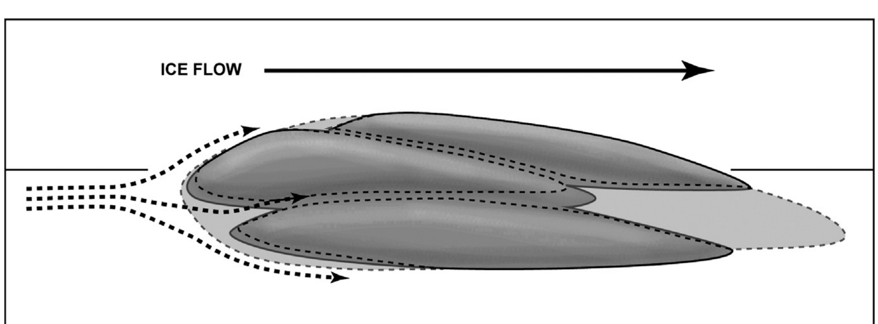

Fig. 5. Schematic model for origin of 'barchan drumlins' where a streaming erodent layer (dotted line) carves grooves into a parent drumlin (Figs. 4A, 9).

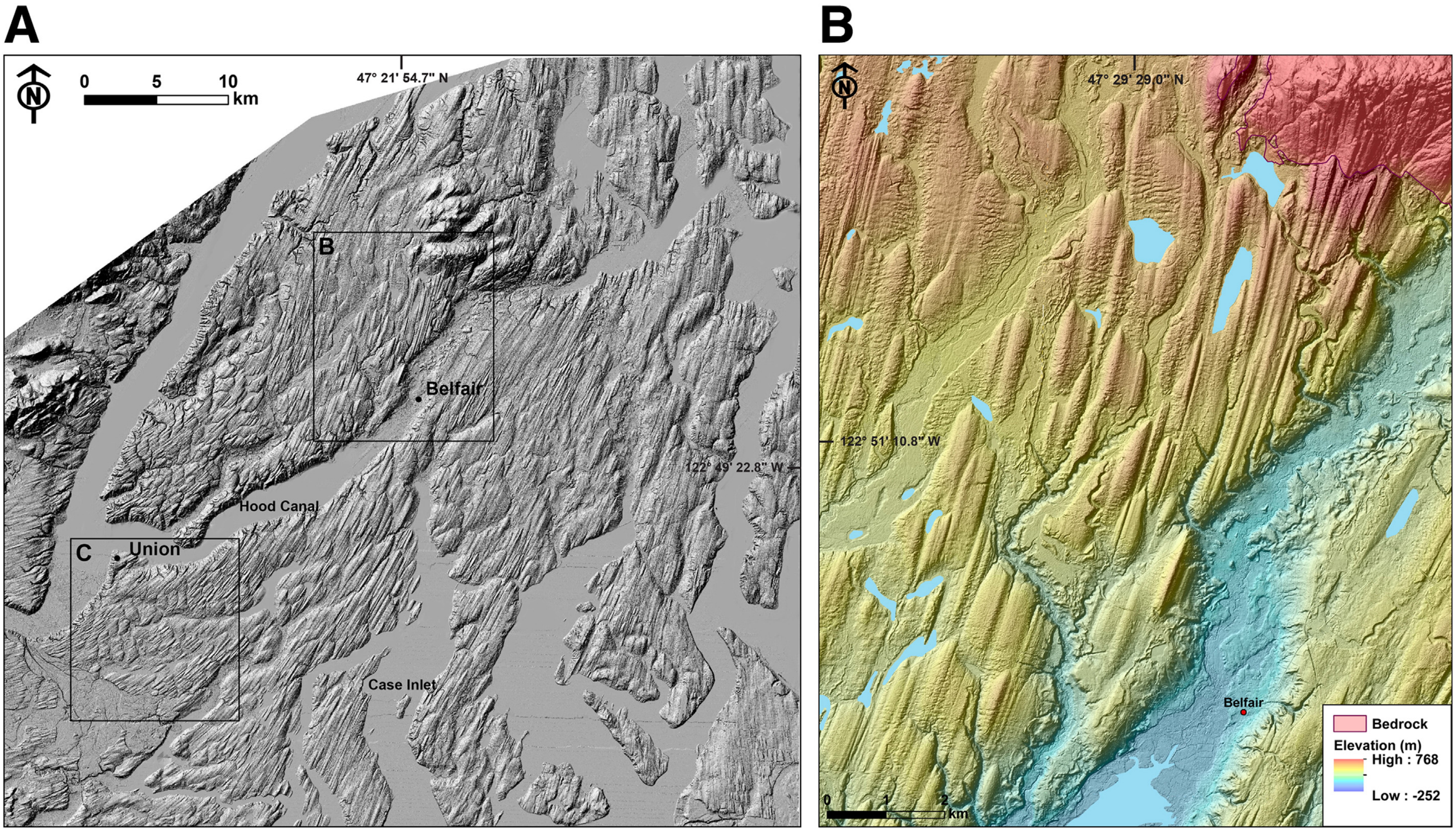

Fig. 6. (A, B, C) LiDAR images of bed of Puget Sound Ice Stream in Washington State with subglacial meltwater conduits (e.g., Hood Canal, Case Inlet). Note transitions from megadrumlins, drumlins and megaridges, carved out of outwash. The flow set contains large areas of megaridged and grooved rock.

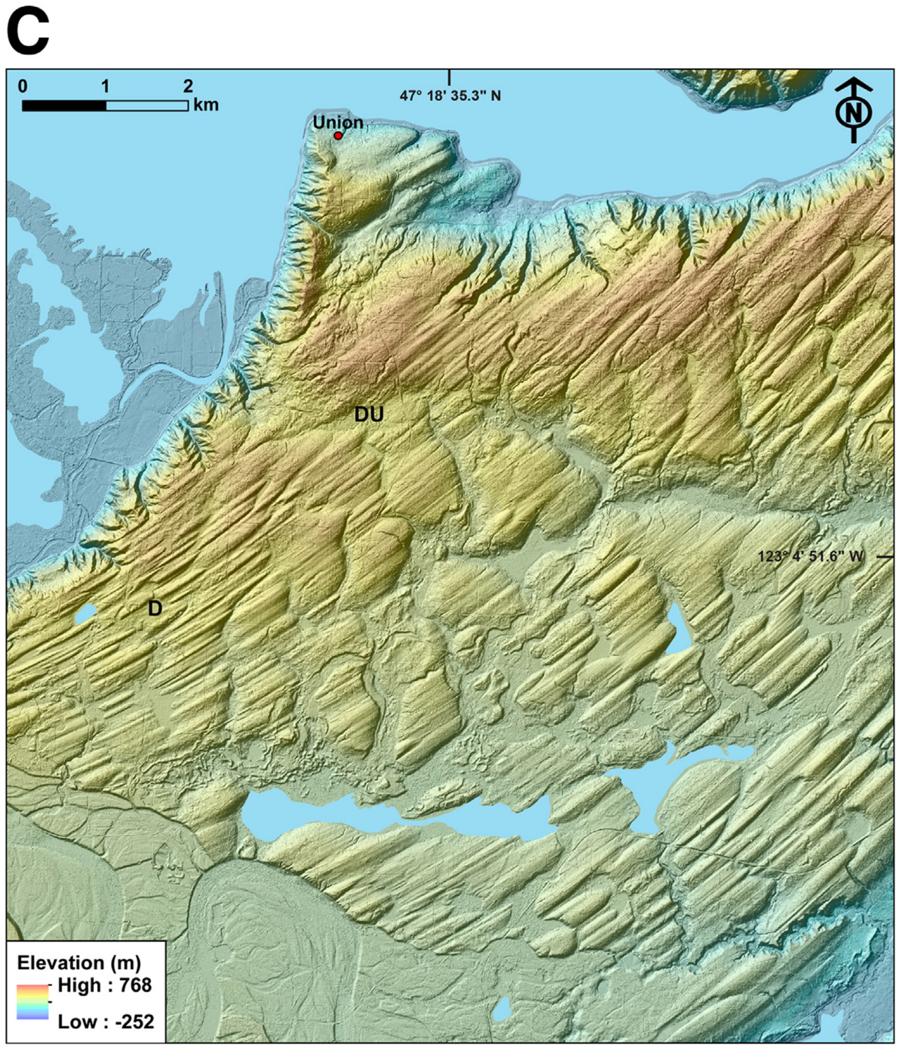

Fig. 6 (*continued*).

4. Drumlins and megaridges produced by erosion: examples

The following sections briefly describe a selected number of glacially streamlined beds from North and South America and Europe that are considered to illustrate the erodent layer hypothesis. Space prohibits a fuller review but some definitive geomorphological, glaciological, geological and sedimentological characteristics are identified that can then be tested against other fields.

4.1. Puget Sound, USA

Newly available LiDAR data reveal that the heavily-forested Puget Lowlands in western Washington State is a 20,000 km^2 corridor of spectacular drumlins and megaridges left by the south-flowing ~200 km long, ~300 m thick, and very short-lived (c. 1500 years) Puget Lobe (Fig. 6A–C). This lobe is tentatively identified here as an ice stream of the main Cordilleran Ice Sheet during the final Vashon Stade of the Late Wisconsin Fraser Glaciation (Thorson, 1980; Brown et al., 1987; Booth, 1994; Booth and Goldstein, 1994; Booth et al., 2003; Easterbrook, 2003; Troost and Booth, 2008; Troost et al., 2005). Ice did not enter the lowlands until c. 17,000 BP and the southern limit of MSGL marks the maximum extent of the Puget Lobe sometime around 15,000 BP.

Goldstein (1994) described Puget Lowland drumlins as being primarily composed of till and regarded them as accretionary bedforms. Examination of LiDAR data together with surficial mapping and study of outcrops provides a much clearer picture of the full range of streamlined bedforms, with well-marked transitions from drumlins to megaridges and their geology (Fig. 6). An important test of the erodent layer hypothesis is that drumlins and megaridges occur on both sediment and rock, and furthermore that the surface till (Vashon Till) is discontinuous and absent from large areas of streamlined topography. The dominant sediment type within the cores of drumlins and megaridges is glaciofluvial outwash (Esperance Sand Member of the Vashon Drift; Booth, 1987; Booth and Goldstein, 1994, p. 210). Geologic data also indicate the widespread presence of large areas of streamlined rock (Easterbrook, 2003, p. 266; Polenz et al., 2004; Troost et al., 2005). Troost and Booth, 2008 (p. 12) noted that 'even in areas of no till deposition, the land displays megaflutes from the overriding ice' and that the lowlands is a 'sculpted landscape.' This is very reminiscent of the conclusions reached by Clayton and Moran (1974) and Whittecar and Mickelson (1977, 1979) from their work in North Dakota and Wisconsin respectively, where capping till layers (where present) are thin and contribute very little or nothing to the volume of streamlined landforms.

Many drumlins in the Puget Lowlands are conjoined and form distinct *en echelon* groups (Fig. 8) on the surface of large 'megadrumlins' (Fig. 6B). These are likely the product of the partial incomplete streamlining of an inherited paleotopography of

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meltwater channels and interfluve surfaces of the former proglacial outwash plain that was overridden. The cloning of megaridges from drumlins is clearly displayed within the axial part of the lowlands (Fig. 6C) in the manner indicated schematically on Fig. 3A.

Elsewhere across the bed of the Cordilleran Ice Sheet in Canada, Lesemann and Brennand (2009) report the stratigraphy of drift drumlins in central British Columbia. They clearly showed that pre-existing sediment is truncated by the drumlin surface indicating an erosional origin, in common with closely associated rock drumlins. McClenagan (2013) also argued that drumlins regardless of core type are 'streamlined erosional residuals.' Lesemann and Brennand (2009) and McClenagan (2013) however, invoked subglacial erosion by catastrophic subglacial outburst floods (e.g., Shaw, 2002) a model rejected by Stumpf et al. (2014). The presence of closely juxtaposed rock and sediment drumlins is the expected outcome of abrasion and streamlining below a subglacial erodent layer moving across a 'mixed bed' of rock and antecedent sediment. There are many other examples of streamlined and megagrooved rock in northern and western Canada, some of which have been interpreted as the product of megafloods (e.g., Munro-Stasiuk and Shaw, 2002), that can be ascribed to direct abrasion and erosion by subglacial debris (Krabbendam et al., 2016).

4.2. Green Bay, USA

One of the largest concentrations of drumlins (~10,000) anywhere in North America occurs west of Lake Michigan in Wisconsin and Illinois, where the downglacier extent of individual fields is demarcated by large till-cored end moraines. These fields record the advance of the Green Bay and Michigan lobes out of the Michigan Basin toward the south and southwest at the Last Glacial Maximum (LGM) with lobe recession subsequently beginning about 15,500 BP (Colgan, 1999; Socha et al., 1999; Krist et al., 2004; Syverson and Colgan, 2004). The consensus is that Green Bay lobe drumlins (Fig. 7) are the product of the subglacial erosion of pre-existing materials either till, stratified sediments and rock or some combination of all three (Upham, 1892, 1894; Patterson et al., 2003). Whittecar and Mickelson (1977, 1979) concluded their study involving numerous exposures through drumlins by stating that their 'shape ….. is due primarily to erosion of pre-existing glacial deposits' as had Alden (1905, 1918) before them. Colgan and Mickelson (1997) argued that 'whatever the agent, erosion seems to be an important process in the drumlin zone' of the Green Bay lobe. Colgan et al. (2003) confirmed that 'many drumlins show evidence that widespread subglacial erosion carved them out of pre-existing sediments.' According to Winguth et al. (2004, p. 35) 'most sediment in them appears to predate the drumlin-forming phase.' A surface till be-

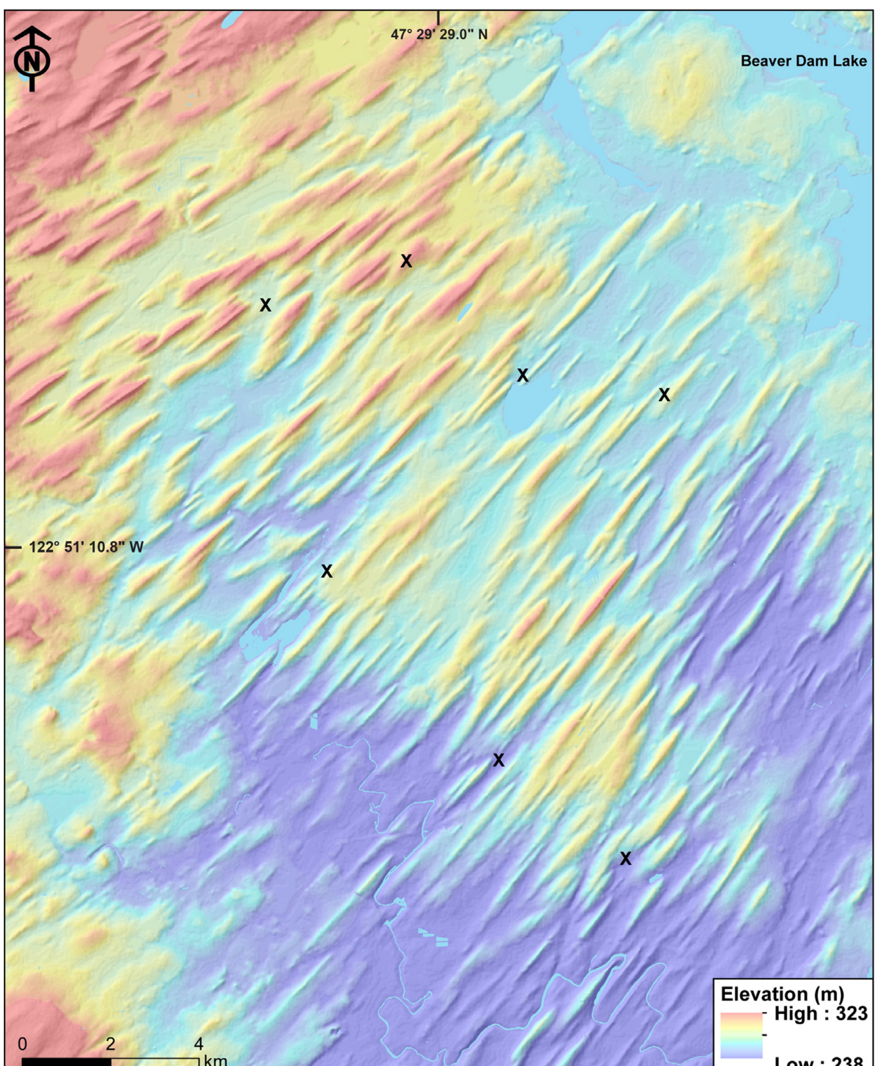

Fig. 7. Cloned drumlins (X) on part of the bed of the Green Bay lobe, Wisconsin. Many different morphological types were identified by Alden (1905). DEM data are from the Geodata directory of the Department of Natural Resources of Wisconsin.

tween 1 and 3 m thick forms a carapace to the drumlin form and can now be recognized as a former erodent layer that accreted at a late stage in the glacial cycle; in this regard it can be considered as a 'retreat till' (Whittecar and Mickelson (1979, p. 369). Colgan and Mickelson (1997) proposed that streamlined bedforms (drumlins, flutes) of the Green Bay Lobe in Wisconsin are the result of the erosion of pre-existing (possibly frozen) sediment (see Cutler et al., 2000) noting that many large drumlins though many meters in height are cored by outwash with a thin carapace of till. They argued (p. 23) that 'net movement of deforming unfrozen sediment out of the drumlin zone' was responsible for erosional shaping of the sediment substrate. In an exhaustive and deeply impressive piece of work, Alden (1905) identified many variations in size, form, and height of what can now be recognized as 'cloned bedforms' left by the Green Bay lobe which he classified simply into what he called 'single,' 'double-tailed, double and triple-crested' and 'drumlin twins and triplets' (see his Figs. 3, 4) and Fig. 7. His work is a rich field for further study.

4.3. Patagonia

Tracts of drumlins and megaridges including glacially-streamlined rock forms, are common along the floors of the major outlet valleys of the eastern margin of the southern Andes in South America. Clapperton (1989) described a very large flow set of drumlinized and megalineated lowland topography (now broken into discrete areas by waterways and rivers) around the inner northeastern part of the Straits of Magellan immediately northeast of Punta Arenas in the southernmost part of Chilean Patagonia (Fig. 12A). Large end moraines at its downstream limit record the furthest extent of an east-flowing lobe (Magellan-Otway Lobe; Benn and Clapperton, 2000b) of the last glaciation Patagonian Ice Sheet that formed over the Andes and its foothills, toward the Atlantic Ocean (e.g., Benn and Clapperton, 2000a,b; Rabassa et al., 2011). The area is highly significant because it contains clear evidence of subglacial bedform evolution on an eroding bed of antecedent sediment. The elliptical form of numerous spindle-shaped drumlins and megaridges (as much as 2 km long) has been modified by straight lateral grooves and longitudinal hollows along their crests ('compound drumlins'; directly analogous to the 'complex' drumlins of Crozier, 1975). Others had been modified along only one of their margins resulting in a distinct asymmetrical cross-section and plan view shape analogous to almost having been cut in half longitudinally to form a 'half ellipse' asymmetrical around their long axis ('asymmetric drumlins'; Figs. 4F, 12B).

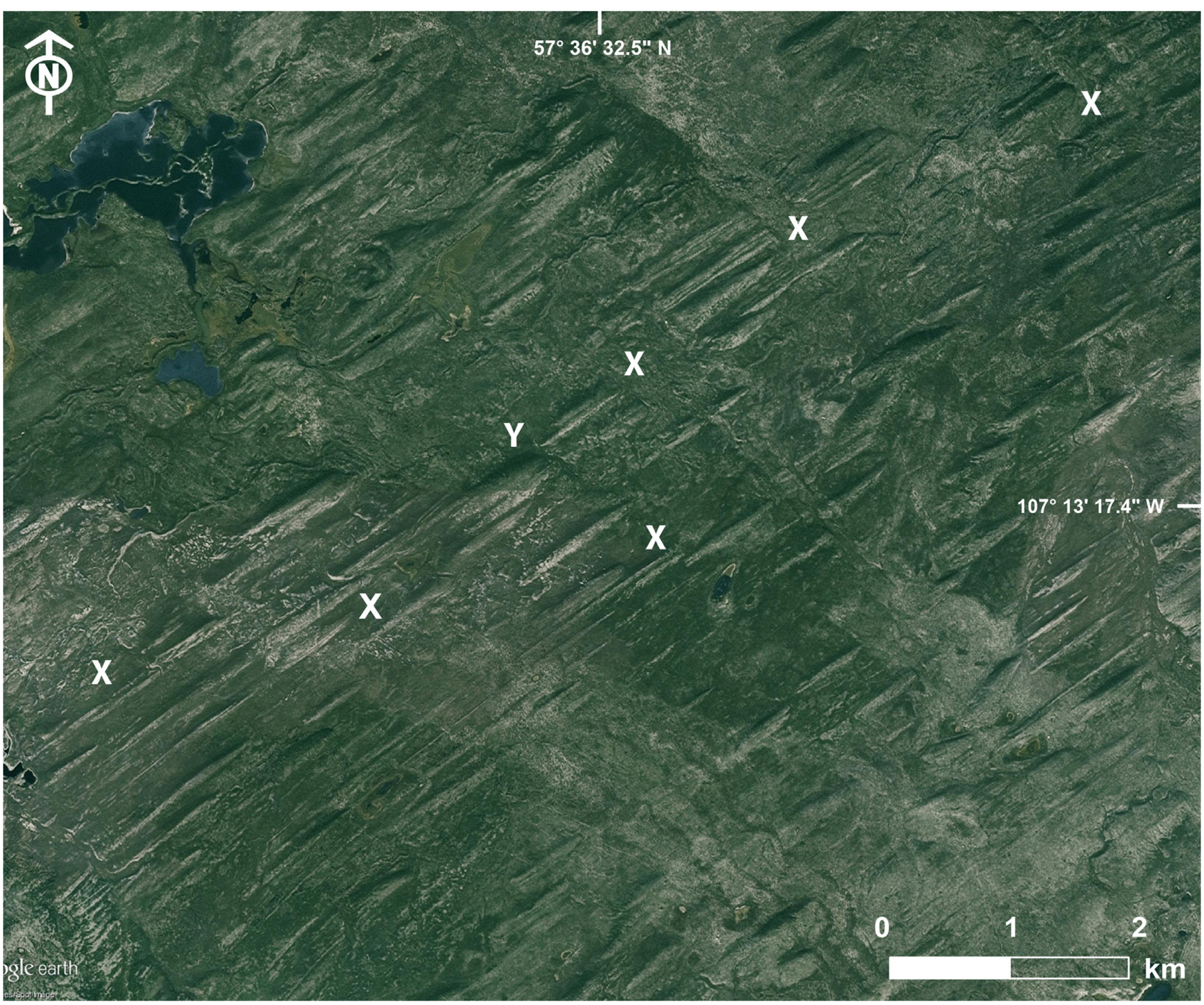

Fig. 8. Area south of Great Slave Lake in the Northwest Territories (NWT) showing cloned drumlins and megaridges (X) resting on bedrock. These bedforms retain a core of antecedent sediment that elsewhere has been stripped to expose bedrock. Note barchan-shaped drumlin (Y) (see Fig. 9). Ice flow from top right.

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Clapperton (1989) presented subsurface data that indicate that the drumlin field was carved across a pre-existing landscape composed of glaciofluvial, glaciolacustrine and aeolian sediment. Till is discontinuous and is present only as a very thin (max 6 m) 'carapace' (Benn and Clapperton, 2000b, p. 595) relative to drumlin height (up to 30 m); the bulk of the bedforms appear to be antecedent glaciotectonized sediment truncated by the till cap (Benn and Clapperton, 2000b). This stratigraphy was interpreted as evidence of initial near ice-marginal glaciotectonism of proglacial sediment and subsequent erosion under fast flowing ice ('ice streaming'; Benn and Clapperton, 2000b, p. 595) toward the axis of the Magellan-Otway Lobe. They also noted the existence of Rogen-like 'cupola hills' (poorly streamlined masses of glaciotectonized sediment) along the margins of the same flow set.

The asymmetric drumlins and megaridges of Clapperton (1989) can be interpreted here as 'hybrid' bedforms whose lateral flanks and crests were being partially eroded by a spatially-discontinuous erodent layer broken down into sub-streams. This process was arrested by final deglaciation and in the process, the elimination of larger subglacial forms to produce narrower more elongated megaridges was curtailed leaving 'half ellipse' drumlins (Fig. 4F). Clapperton (1989) noted a tendency for drumlins to be modified on their southeast margins; it can be speculated that this may indicate an anticlockwise (northwards) migration of ice flow direction and accompanying changes in erodent layer vectors accompanying a shift in ice flow direction. Such asymmetric streamlined bedforms may ultimately prove to be the geomorphic expression of incipient late stage 'flow switching' during deglaciation involving lateral corrosion by an erodent layer now being forced to move in a different direction and modify its bed accordingly.

5. Clones: the missing link in the drumlin–megaridge continuum

Clark et al. (2009, p.690) concluded that the notion of a 'bedform continuum' from drumlins to megascale glacial lineations is an 'appealing and important idea (pointing at a single mechanism of formation?) and appears to have wide support, but it actually remains an open question.' ELH proposes that the answer lies in the subglacial lowering of the original subglacial sediment bed by erosion allowing the replication of successively narrower and more elongate genetically-related bedforms by cloning (Figs. 2, 3A). The concept of a genetically-related bedform continuum was broadly anticipated by Lundquist (1970), Sugden and John (1976), Aario (1977) and Rose (1987) but close examination of Aario's now classic and widely-adopted illustration indicates that it depicts abrupt step-like boundaries between transverse (Rogen) bedforms, drumlins and megaridges rather than any true continuum. Correspondingly the classic Aario figure can be revised to show a continuum between bedforms as a result of continued cloning accompanying overall lowering of an antecedent bed (Fig. 13).

Large Rogen moraines, and megadrumlins (also variably called 'drumlin shields,' 'drumloids' or 'drumlin uplands' by some workers e.g., Thwaites, 1961; Glückert, 1973), can be said to be the progenitors or parents of drumlins. These more substantial landforms survive because they have not been sufficiently lowered, dissected and cloned (Fig. 3A). The presence of relict buried moraines for example, preserved below drumlins is widely reported (e.g., Kleman et al., 1997; Möller, 2006; Finlayson et al., 2010; Kleman and Applegate, 2014; Trommelen and Ross, 2014). Benn and Evans (2010; their Fig. 11.23c) specifically identify 'transverse asymmetric drumlins.' These can be identified as remnant patches of antecedent sediment (such as moraines) lying transverse to ice flow (e.g., Fig. 4G) that were overrun and only partially streamlined; this situation can also be clearly discerned from Fig. 1b in Clark (2010; Fig. 3B). The same sequence of events was briefly suggested by Ottesen and Dowdeswell (2006) for drumlinized and megalineated surfaces exposed on the sea floor by the retreat of Borebreen in Svalbard where an antecedent morainal topography that existed prior to subglacial streamlining is still clearly evident.

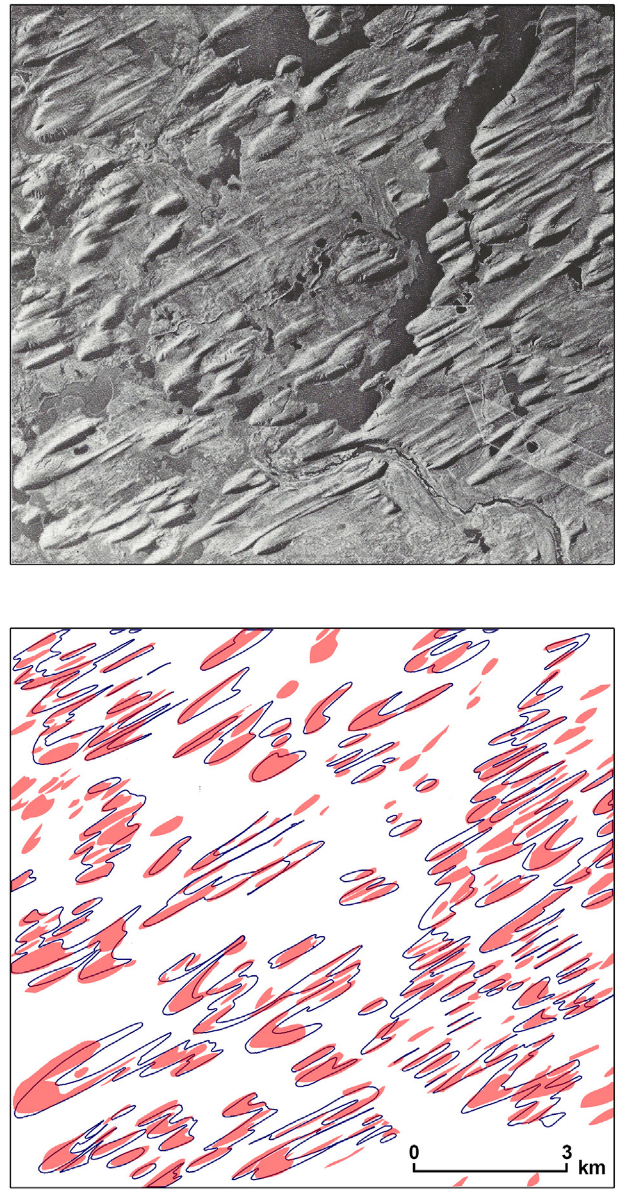

Fig. 9. Top: Drumlins around Snare Lake, NWT display a 'barchan-like' form previously attributed to large-scale folding and downglacier movement of deforming sediment around a stable core (blue line on bottom figure after Boulton, 1987). Re-mapping (red line on bottom figure) indicates these are conjoined 'cloned' drumlins carved from in-situ pre-existing sediment (Fig. 5). Ice flow to top right.

The glacial overriding and erosional dissection of antecedent sediment masses and associated landforms provide a ready explanation for why many drumlins are not randomly distributed spatially but are often found grouped together as distinct 'clusters' within drumlin fields (Hill, 1973). ELH predicts this non-systematic distribution simple reflects a control on the location of drumlins arising from the necessary requirement of a sediment bed to be sculpted and is inherited from the incomplete streamlining of an antecedent topography of moraines, channels, bars, interfluves, or lake depressions (e.g., Krüger, 1987; Boulton, 1987; Smalley and Warburton, 1994; Kjaer et al., 2003). The presence of thick sediment will dictate the location of initial megadrumlins which reflects the selective preservation of thicker sediment in topographic lows. These higher standing landforms are eliminated as ice flow increases, indeed their destruction is a fundamental pre-requisite for ice streaming. The bed is lowered and carved by successive cloning to form a 'low-slip' megaridged surface (Fig. 3A).

A drift drumlin is an obstacle to ice flow. The strongest part of the bedform occurs on its upstream stoss side which protects sediment within the tail. Many drumlins have lunate-shaped crescentic overdeepenings ('frontal grooves') that wrap around their stoss side and which are widely interpreted as the product of subglacial meltwaters (see review by Livingstone et al., 2012, p. 103). However, in keeping with the ELH model proposed herein, these frontal grooves more likely record enhanced erosion at the base of faster moving sub-streams of erodent layer debris forced to diverge around the stoss side of the drumlin. The process was described by Eyles (2012) in the case of rock drumlins. By comparison to the stoss side, drumlin tails are relatively weak and limited data appear to suggest they are more susceptible to removal such that the bedform as a whole may be 'hollowed out' by removal of sediment from its rear end which will be preferentially lowered compared to its stoss end. This results in a hybrid drumlin 'triplet' (so-called 'barchan drumlins') with a 'central depression' and lateral 'wings' of smaller drumlinized masses (Figs. 4A, 5). This very distinctive type appears to be a recurring bedform in nearly all drumlin fields (Fig. 8) and is an indication of the importance of erosion in drumlin formation.

The Snare Lake drumlin field of northern Saskatchewan shows many barchan-type drumlins with downglacier directed limbs (Fig. 9). Drumlins are cored by remnants of ice-proximal glacial outwash suggesting that ice overran and streamlined antecedent proglacial deposits (but see Shaw, 1983; Shaw and Kvill, 1984; Shaw et al., 2000). Notably, many drumlins and megaridges are isolated bedforms that sit on a low relief bedrock surface that is itself also streamlined. Boulton (1987, p.66) suggested that barchan drumlins are the result of wholesale bed deformation involving the downglacier movement *en masse* of 'wings' of deforming sediment on both sides of a more stable core; forming what Benn and Evans (2010) describe as 'strongly deforming sediment streaks' (p. 471) around more resistant cores. Boulton's model essentially interpreted their barchan-like morphology as large-scale 'shear folds' (his Fig. 24b) in keeping with his idea that drumlins are migratory bedforms produced by folding around a stable core. Re-mapping of these bedforms shows that the supposed barchan shape of many drumlins is exaggerated (Fig. 9) and that they are rigid stable autochthonous bodies of drumlinized sediment in the process of being lowered by erosion and cloned into daughter drumlins and ridges by a streaming erodent layer (Fig. 5).

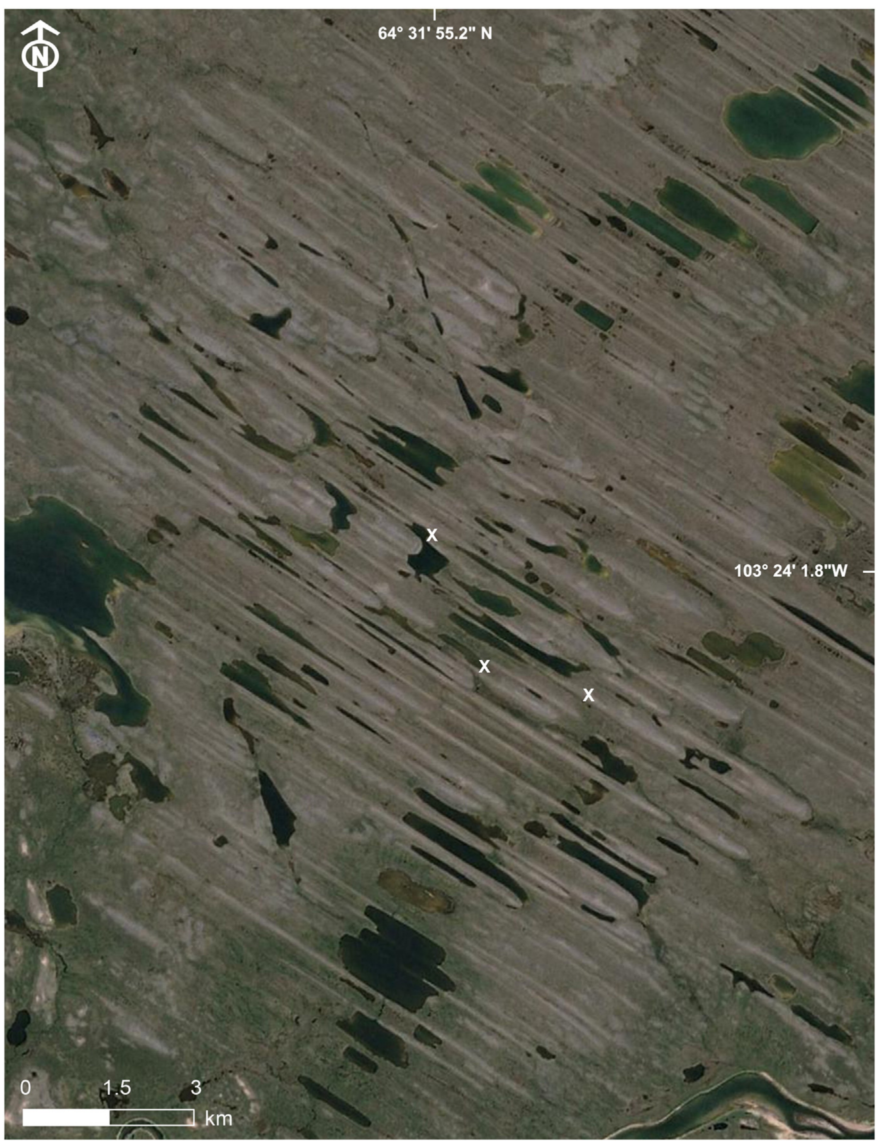

Fig. 10. The bed of the Dubawnt Lake Ice Stream, NWT shows numerous 'cloned' drumlins (X) resting on large areas of exposed bedrock. The ELH model on the argues that this as an erosional landscape of pre-existing sediment, lowered by streamlining and cloning (Fig. 3A) to produce a low-slip surface that enabled fast ice flow. Satellite imagery extracted from Google Earth (2013). Ice flow to top left.

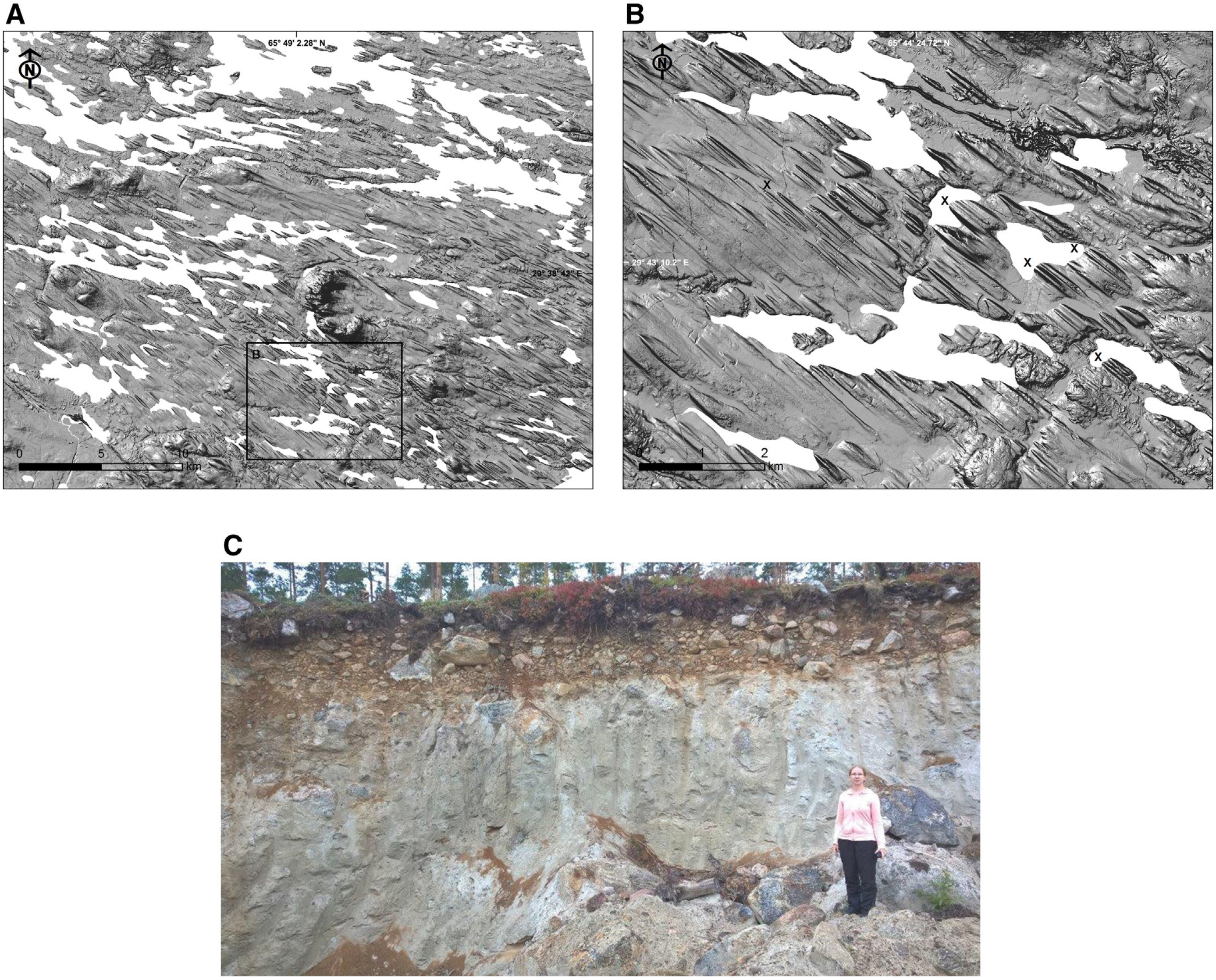

Fig. 11. (A, B) Portion of Kuusamo drumlin field in Central Finland showing water bodies (white), emergent bedrock highs protruding through drift cover, and cloned drumlins (X). LiDAR Data from Geological Survey of Finland. (C)Outcrop through drumlin showing former erodent layer preserved as a till cap that truncates antecedent till below.

At Snare Lake, barchanoid drumlins likely record the last stages of the erosional lowering of a previously extensive glaciofluvial sediment cover from underlying rock which is now exposed over large areas of the bed. Drumlins and associated elongate megaridges preserve vestiges of this once continuous cover in their cores. Indeed, the conclusion of the most detailed field study of megaridges to date in northwest Canada by Stokes et al. (2013a) and Ó Cofaigh et al. (2013) suggests that tracts of mega-scale glacial lineations left by the Dubawnt Ice Stream could be in situ remnants of an older autochthonous till sheet. O Cofaigh et al. (2013) also drew attention to the presence of horizontally-stratified sediment cores in some ridges that could not have undergone deep, pervasive substrate deformation required by the instability model (see Fig. 8a in O Cofaigh et al., 2013). The observation of numerous cloned megaridges (Fig. 10) supports the view that the entire landscape is erosional in origin (Fig. 3).

In Europe, cloned drumlins and related megaridges are widespread across some 25,000 km^2 of the Fennoscandian Shield in Central Finland such as across the Kuusamo drumlin field (Fig. 11A, B), in a setting directly comparable to the Athabasca Basin of Canada. Many are 'obstacle drumlins' of Clark (2010) composed of sediment preserved in the lee of rock knobs (and also in the stoss side e.g., the 'pre-crags' of Glückert, 1973, 1974; Haavisto-Hyvärinen, 1987; Haavisto-Hyvärinen, et al., 1989; Nenonen, 1994, 1995). Such forms likely result from preferential survival of pre-existing sediment around bedrock highs that are progressively being exposed by bed lowering in contrast to preferential deposition of sediment around such highs. In this regard, further work is needed to assess the evolution of bedforms where an initial thick 'soft' subglacial bed of sediment is stripped and lowered to create a 'mixed bed' by the exposure and emergence of bed rock highs.

Cloning of drumlins and megaridges from megadrumlins underlain by pre-existing sediment (the 'drumlin shields' and 'drumloids' of Glückert, 1973) is widespread and exposures through drumlins show a coarse-grained, lithologically distinct, thin till 'cap' (the preserved erodent layer) cut across cores of antecedent tills of very different lithology (Fig. 11C) confirming an erosional origin (see also Sutinen et al., 2010). Continued cloning and replication as the subglacial bed is lowered by erosion ultimately results in more numerous, more closely-spaced, narrower and topographically-lowered megaridges. This stage marks the ultimate development of a low slip, and low friction 'slickenlined' surface (Fig. 3A) expressed geomorphologically as long, low relief megaridges with a mean lateral spacing of 200–300 m (Spagnolo et al., 2012, 2014). Large areas of scoured bedrock are exposed between megaridges signifying almost complete removal of sediment (e.g., Fig. 8) accompanying the formation of a mixed bed.

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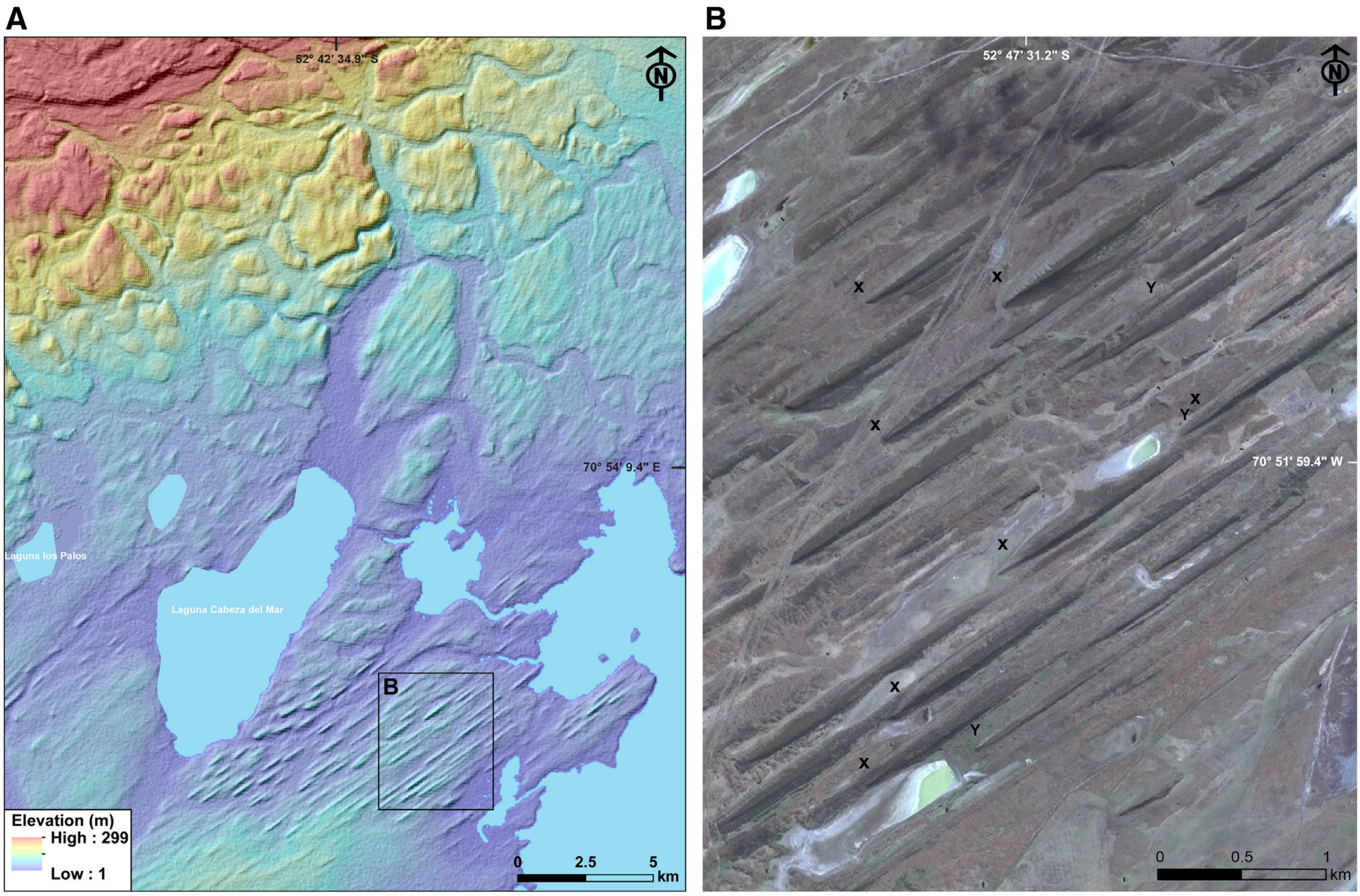

Fig. 12. (A) Flow set composed of megadrumlins (at top of image; called 'cupola hills' by Clapperton, 1989) transitional downflow to drumlins and megaridges near Laguna Cabeza del Mar, southern Chile produced by erosional streamlining of outwash and glaciolacustrine sediment (Fig. 3A). (B) 'Asymmetric drumlins' of Clapperton (1989) showing 'half-elliptical' form (Fig. 4F) with a straightened lateral margin and deep groove recording lateral corrosion by an erodent layer (X). Note bisected drumlins with central grooves (Y) (e.g., Fig. 4D). Data from GeoSUR Regional Map Service Viewer for South America (http://www.geosur.info/map-viewer/index.html?config=config-rms-en.xml&lang=en_EN).

6. Discussion

ELH does not claim to provide a comprehensive model for the formation of drumlins and megaridges. Nor is it intended to de-emphasize the possibility of equifinality and the possible role of depositional processes that might also help nucleate and grow these bedforms (e.g., instability model: Stokes et al., 2013a,b). The ELH hypothesis is as yet, challenged by a lack of quantitative modeling and testing. A major strength of ELH however, when compared to other models, is that it simply re-emphasizes and enlarges upon a wealth of unambiguous geological evidence reported by many workers that subglacially-streamlined bedforms are entirely erosional in origin. Drumlin cores are widely composed of non-deforming or horizontally stratified sediments that are abruptly truncated by the drumlin form; drift drumlins and megaridges also occur as part of a 'mixed bed' with closely associated drumlins and megaridges made of rock and are commonly flanked by exclusively 'hard beds' composed of rock-cut drumlins and megaridges. The ELH hypothesis is also based on geomorphological evidence that drumlins and megaridges form an erosional continuum by identifying 'clones' as missing links in an evolutionary succession (Fig. 3A). The almost ubiquitous presence of clones in drumlin fields indicates the broader significance of the erosional model presented herein and the importance of erodible sediment and or rock to the evolution of megaridges from drumlins. Given these considerations, it does seem very implausible that models emphasizing bed deformation and wave-like instabilities of the ice-till bed interface can be said to represent 'a final resolution of the centuries-old problem of drumlin genesis' (Clark, 2010, p. 1011). It is a reasonable view instead, that these bedforms arise from some combination of deposition and erosion that varies spatially and temporally at the base of ice sheets; the instability hypothesis emphasizes the constructional role of deformation on a soft till bed, ELH stresses the opposing role of excavational deformation and erosional streamlining across all substrates. In this way, ELH possesses the broader capability to explain the presence of drumlins and megaridges on rock, till, other sediments and any combinations thereof, thereby more widely reflecting the actual geology of continental ice sheet beds.

What follows is a brief discussion of the characteristic stratigraphy of erosional streamlined bedforms to guide further investigations and testing of the ELH model.

6.1. Caps and cores

Both Armstrong (1949) and Dean (1953) invoked a 'two-phased' erosional model for drumlins where a pre-existing till sheet was subsequently reshaped into drumlins. Dean (1953) linked the formation of drumlins to a 'rapid drumlinizing event' (p. 28) marked by an abrupt increase in ice velocity; the same model is implicit in 'drumlinization events' noted by others accompanying the onset of ice streaming and fast ice flow late in the glacial cycle (e.g., Eyles and McCabe, 1989; Knight and McCabe, 1997). In those cases where drumlin cores consist of thick, stiff, highly overconsolidated till, it can be suggested that the core is a remnant of an originally much more extensive till sheet deposited during an earlier glacial phase that was subsequently streamlined by erosion under a different glacier flow regime. Correspondingly,

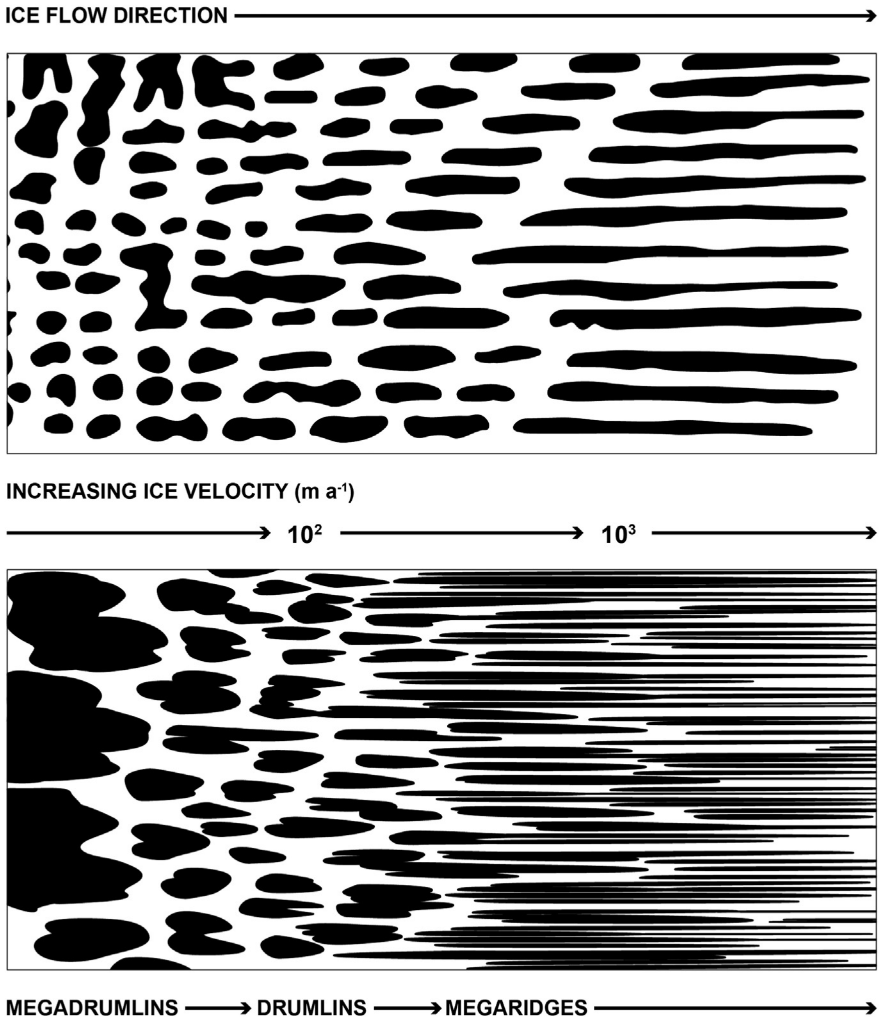

Fig. 13. Top: Subglacial bedform diagram of Aario (1977) as partly modified by Stokes et al. (2013a, b) showing step-like changes from one bedform type to another. Bottom: Revised figure recognizing clones as 'missing links' in the continuum between megadrumlins, drumlins and megaridges that records accelerating ice flow velocities and ice streaming (Fig. 3A).

many reported drumlin cores consist of truncated rock or pre-existing sediment with only a relatively thin (<3 m) till 'carapace' draping the drumlinized unconformity below and variably called a 'cap till', 'upper till', 'till veneer', 'till mantle', 'retreat till' or interpreted as 'englacial debris' by previous workers (see the wide-ranging review by Stokes et al., 2011)(Figs. 11C). This cap commonly has a lithological composition (and fabrics; e.g., Vreeland et al., 2015) very different from thicker core tills below and it can be speculated that it is the result of ice deceleration and in situ thickening of an erodent layer during deglaciation and the commencement of constructional deformation (e.g., Fig. 1). Johnson et al. (2010) describe the internal structure of drumlins in front of a surge-prone Icelandic glacier where 'the youngest till layer truncates older units with an erosion surface that parallels the drumlin form' (p. 943); the till layer likely acted as an erodent layer when in transport and was then preserved during ice retreat under decelerating ice flows. The same model can be clearly seen in descriptions of the geology of other Icelandic drumlins reported by Krüger and Thomsen (1984). Schomacker et al. (2006) similarly describe drumlinization of overridden stagnant ice in Iceland which is an unusual type of 'stiff' substrate shaped primarily by erosion. Newman and Mickelson (1994) describe relict tills and paleosols within the cores of drumlins in Boston Harbor, Massachusetts truncated by a cap till that 'drapes the erosional drumlin form without contributing substantially to relief of the drumlin form.' It may be the case, given the restricted thickness of any preserved erodent layer and likely lithological contrasts with sediments below, that erodent layers have been formerly interpreted as the product of weathering and subaerial reworking of the drumlin surface after deglaciation, and consequently disregarded.

Kleman (1994), Kleman et al. (1997, 2002), Finlayson et al. (2010), Greenwood and Kleman (2010), Knight (2010b), Sutinen et al. (2010), Kleman and Applegate (2014) and Trommelen and Ross (2014) have all highlighted the preservation of old tills and landforms under younger surface flow sets. The presence of 'crossing flow sets' is also noted (Clark, 1993) with major implications for mineral exploration projects. In this context, older 'inherited' mineralized dispersal fans in tills often record very different ice flow directions and source areas from those indicated by surface megalineations (e.g., Mooers, 1990; Trommelen et al., 2013). Drumlin cores exposed in numerous coastal sections in Nova Scotia in Maritime Canada (Stea and Brown, 1989; Stea, 1994) 'reveal thick, predictable drift sequences' (Stea and Finck, 2001, p. 251) consisting of as many as three regionally-correlative tills, which is not the expected outcome if these drumlins were the product of individual in situ accretion. The preservation of consistent sheet-like stratigraphic successions within widely-spaced drumlins is unambiguous evidence of an erosional origin for drumlins.

The widespread occurrence of bipartite drumlin stratigraphies consisting of a 'core and cap' suggests prior accumulation of till sheets (or proglacial sediments) associated with long-term steady-state sluggish ice flow (or different basal thermal regime) followed by erosional lowering of the bed during fast ice flow and drumlinization late in the

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glacial cycle. It can be noted here that ongoing work in Antarctica appears to stress the relative importance of erosion (not deposition) under fast ice flowing ice streams and overall rapid bed lowering (e.g., Smith et al., 2007, 2012). The highly dynamic environment under ice streams also appears to suppress the formation of tunnels and eskers at the ice base (see Dowdeswell et al., 2015, p.1688). These considerations suggest that the growth of accommodation space necessary to allow deposition and aggradation of the bed, is severely restricted or even prohibited under fast flowing dynamic ice masses and act to suppress aggradation of the bed and therefore, the upwards growth of drumlins as postulated elsewhere. These dynamic conditions on the other hand favor erosion and the formation of drumlins and megaridges by growing down into an erodible antecedent substrate as a consequence of bed lowering and debris streaming (Fig. 3A).

Initial till deposition under sluggish ice flow followed by erosional streamlining under fast ice flow is clearly evident in regard to distinct carbonate-bearing till derived from Paleozoic strata that offlap the Canadian Shield around the southern margins of Hudson Bay. Formerly regarded as being regionally continuous (Hicock, 1988; Hicock et al., 1989) carbonate-rich till is now recognized as occurring in the form of 'patches of thick, drumlinized till' (Larson and Mooers, 2005, p. 233) separated by areas of thin, locally derived till and widespread exposure of crystalline bedrock. These authors concluded that patches of carbonate-bearing tills are erosional remnants of a once continuous deposit accumulated earlier in the glacial cycle. It is possible that significant accumulation of carbonate-rich till occurred early only for such deposits to be eroded and drumlinized accompanying the onset of ice streaming late in the glacial cycle. This underlines the need to better understand why, where and when rapid ice flow and ice streaming occurs in large ice sheets (e.g., Möller, 2006; Winsborrow et al., 2010; Möller and Dowling, 2015).

A corollary of the ELH model is that non-streamlined subglacial till plains have been preserved intact upon final deglaciation in those areas unaffected by ice streaming. For example, large parts of the former bed of the Green Bay and Michigan lobes in Illinois, Ohio and Indiana consist of non-streamlined low relief till plains ('ground moraine'; Patterson, 1998; Patterson et al., 2003). They are also a feature of eastern England (Hart, 1997) and can be argued to have been built by constructional deformation under non-streaming 'steady-state' ice flow velocities. Their glaciological significance is that they remained under ice flows of slow or intermediate velocity during the full duration of glacial occupancy and escaped erosion and drumlinization by faster moving erodent layers.

6.2. Drumlins and megaridges: comparison with industrial wear surfaces and other geological analogs

Drumlins and megaridges appear to be a large-scale natural example of the 'surface texturing' that develops on man-made materials undergoing frictional wear (e.g., Bowden and Tabor, 1939; Marmo et al., 2005; Fox-Rabinovich and Totten, 2006; Higgins et al., 2008; Ma and Zhu, 2011; Sedlaček et al., 2011; Bai and Bai, 2014; Baum et al., 2014; Hanaor et al., 2015). Pike (2001) noted what he regarded as an emerging convergence between surface metrology (the numerical characterization of man-made industrial surfaces) and terrain analysis, and introduced the term 'tribology' to physical geographers. This convergence however has never been fully made and has not yet greatly impacted thinking about the evolution of glacial landscapes. By reference to well-established tribological concepts and terminology, drumlins and megaridges are large-scale geological examples of 'wear tracks' resulting from macro-abrasion by 'wear products' between mated surfaces in relative motion. Correspondingly, till can be regarded as a 'wear product' resulting from the comminution of bed substrate materials and which in turn, is moved subglacially as an erodent layer capable of lowering and streamlining the substrate. Geologists already have a term for such wear processes ('cataclasis') and wear products ('cataclasite') and there are several facies descriptive schemes in regard to differing clast and matrix contents that are highly appropriate for describing till-forming processes and resulting till facies (e.g., Woodcock and Mort, 2008). In this regard, till is essentially a 'glacial cataclasite.' Poorly-sorted 'till-like' cataclasites are ubiquitous in the non-glacial geological realm ranging from the basal layers of large mass transport deposits (landslides etc.,) to fault gouge, to the peripheries of meteorite impact craters (pseudotachylite) and the process of cataclasis allows ductile flow within the Earth's upper brittle crust (e.g., Pittarello et al., 2012).

Abrasion between surfaces in relative motion results in the removal of debris from one surface that act as abrasive particles ('erodents' or 'triboparticles') that cut 'wear grooves' on the opposed surface (Shipway and Hodge, 2000; Dove, 2010; Kovalchenko et al., 2011; Ćurković et al., 2011; Hidy and Brock, 2013). Wearing on mated moving surfaces produces grooves (e.g., Rigney, 1988; Hisakado et al., 1993; Hogmark et al., 2007; Kleis and Kulu, 2008; Menezes et al., 2010; Kasem et al., 2010; Narita, 2012; Basavarajappa and Ellangovan, 2012; Basavaraju and Ranganatha, 2013) and streamlined micro-bedforms directly analogous to drumlins (and are similarly called 'microdrumlins' or 'ellipsoidal obstacles'; Komar, 1983; Jiang et al., 1988; Yuan et al., 2011; Brown and Robbie, 2013; Bai and Bai, 2014). Use of 'optimum shape theory' (Whitney, 1972) demonstrates that streamlined forms (such as those of projectiles e.g., bullets or ship's hulls etc.,) become increasingly elongate to allow movement through surrounding media at higher velocities (Sagy et al., 2007). By comparison, in the subglacial realm, the geomorphological continuum from large equant drumlins to extremely elongated megaridges (e.g., Aario, 1977) lessens drag on the ice base and allows faster ice flow as recognized in by Chorley (1959). There are striking morphological affinities between streamlined glacial surfaces with other low friction corrugated surfaces such as the riblets and grooves on aircraft wings and other surfaces (e.g., Baum et al., 2014).

Streamlined bedforms directly comparable to subglacially-produced megaridges are also produced by erosion at the base of fast-moving gravity-driven masses of sediment or broken rock, and also along faults. Debris flows, slumps, rock avalanches, megabreccias, landslides or pyroclastic flows all have basal erodent layers of crushed cataclastic debris containing outsized erodents. This layer allows the overlying mass to move more easily over the substrate and in the process, to cut a low slip surface of ridges and grooves on the underlying surface. Megagrooves and ridges occur at the base of modern and ancient Mass Transport Deposits (MTDs) from both outcrop and seismic data (e.g., Brey and Schmincke, 1980; Cas and Landis, 1987; Gee et al., 2005; Johnson and Cotton 2005; Shea and van Wyk de Vries, 2008; Draganits et al., 2008; Posamentier and Kolla, 2003; Campbell and Mosher, 2010; Dakin et al., 2013). Large landslides on Earth and Mars show surface ridges and grooves oriented parallel to flow that recording fingers ('sub-streams') of debris moving at different velocities within the flow (e.g., Shreve, 1968) reflected in the cutting of grooves on the base of flows comparable with glacial megaridges. Gee et al. (2006) describe megagrooves and ridges formed by large tools (bedrock rafts and boulders) on the base of a very large (430 km^2) submarine landslide having individual depths of as much as 15 m and lengths of 9 km directly analogous to their glacial counterparts. The only limit to their length is the downslope run out distance of the MTD. Submarine landslide-related grooves and remnant sediment ridges described by Posamentier and Kolla (2003) are 700 m wide, 40 m deep and several kilometers long on a scale comparable to the average height and lengths of their glacial counterparts (see also Draganits et al., 2008; Posamentier and Martinsen, 2011; Shipp et al., 2011). Sparks et al. (1997) describe parallel 'erosional furrows' associated with streamlined and striated bedrock cut below a high temperature erodent layer at the base of a pyroclastic flow at Lascar Volcano, Chile. Erosional furrows cut by clast-rich zones within an internally segregated pyroclastic flow have also been observed at Mt. St. Helens (Kieffer and Sturtevant, 1988).

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Faults commonly display large grooves and ridges directly comparable to glacial examples, including the presence of abraded 'bullet-shaped' clasts (Engelder, 1974a,b; Eyles and Boyce, submitted for publication; Carena and Suppe, 2002; MacLeod et al., 2002; Marshall and Morris, 2012). Sagy et al. (2007) described and illustrated 'elliptical bulges' on fault planes perfectly analogous to drumlins and showed how such forms become straighter and evolve into 'fault striations' (i.e., similar to the drumlin-megaridge continuum) with increased slip. In the process, poorly-sorted cataclastic fault gouge (equivalent to deforming subglacial 'till') is sheared and mobilized under very high crushing pressures between moving fault blocks (Engelder, 1974a,b; Sleep and Blanpied, 1992). In rock mechanics terminology this is referred to as 'matrix-controlled cataclastic flow' and produces a 'cohesive cataclasite' which in essence, is a lubricating layer capable of erosion. The presence of large-scale grooved surfaces on detachment faults was reported by McLeod et al. (2002) from submarine outcrops of the exposed plane of a gently-dipping detachment fault on the margins of the mid-Atlantic Ridge (see also Cann et al., 1997). They describe corrugated rock surfaces 'in the form of elevated ridges tens of meters wide, hundreds of meters long, and <10 m in relief elongated parallel to the spreading direction. The surfaces of these outcrops are smooth and covered with centimeter-scale striations, also parallel to the spreading direction' (McLeod et al., 2002, p. 880). This is a description of rock-cut megaridges on detachment faults that are directly comparable in form and scale to subglacially-streamlined counterparts on hard beds.

Finally, the similarity in form and size between megaridges and mega-yardangs can also be noted. The latter are produced by unidirectional flows of abrasive material (sand) swept along by persistent wind (e.g., Goudie, 2007; Kapp et al., 2011). This is analogous to the action of an abrasive erodent layer formed subglacially. Essentially, all these landforms grow down into the substrate.

The presence of drumlin-like microforms on man-made wearing surfaces, and larger streamlined macroforms at the base of mass flows and on faults suggests that glacially-megaridged surfaces are essentially 'megaslickenlines' formed by abrasion of an erodible substrate by an erodent layer (deforming till). This results in a low slip surface that allows fast ice flow. This finding was anticipated in part by Smalley et al. (2000, p.32) who stated that the 'ground interface/glacier system organizes a flow-promoting ground geometry, which we call a 'drumlin field' designed to lower drag.' Clark (2010) and Spagnolo et al. (2014) have also briefly alluded to 'spatial self-organization' in drumlin fields. Frictional retardation between the bed and overlying ice is reduced by the elimination of higher standing obstacles (drumlins) to form narrower longer features (megaridges; essentially slickenlines) thereby increasing its 'slipperiness' allowing faster ice flow and streaming.

In short, the above discussion of a large body of work emanating from a variety of scientific disciplines shows that analogous streamlined micro- and macro-forms are produced by wear on all sliding surfaces. This underscores the 'fundamental similarity between all forms of sliding whether on the massive geological scale or on the microscopic scale' as proposed by Stachowiak and Batchelor (2014, p.3) and opens the way for quantitative physical modeling of the wear processes that produce drumlins and megaridges under large continental ice sheets by erodent layers.

7. Conclusions

The erodent layer hypothesis (ELH) proposes that drumlinization is primarily an erosional process that leaves no substantial stratigraphic record because it cuts a streamlined unconformity surface across pre-existing bed materials. A review of the literature and use of appropriate examples of glacially-streamlined terrains from North and South America and Europe, confirms that many (most?) drumlins are residual features made of antecedent sediment or rock and 'grew down' into the underlying bed of ice sheets as a consequence of abrasion by a layer of deforming subglacial debris. This debris is defined as an 'erodent layer.' Such debris is a 'glaciogenic cataclasite' which lubricates ice flow but which significantly is also capable of erosion along its lower bounding surface when dragged across the underlying substrate ('erosional excavation').

ELH proposes that the drumlin-megaridge continuum is the expected outcome of the erosional dissection ('cloning') of large parent drumlins originally formed under sluggish or steady state ice flows, by narrow sub-streams of an erodent layer under accelerating ice flow velocities. Successive cloning and lowering of the antecedent subglacial surface create more elongate daughter bedforms and ultimately, a low-friction megaridged surface that allows even faster ice flow and ice streaming. In this fashion, drumlinization and cloning do not leave a substantive stratigraphic record other than a thin, discontinuous carapace of till (commonly described as 'till caps', 'till carapaces', 'till veneers', 'upper tills', 'englacial debris' etc.,) resulting from subsequent decelerating ice flows ('constructional deformation') during final deglaciation. The presence of thicker tills within drumlin cores likely records dissection of older till sheets that accumulated under sluggish or steady-state non-streaming ice flows earlier in the glacial cycle. Much more work is now needed on the subsurface *geology* of subglacially-streamlined beds to identify the varying relationship between zones of subglacial erosion and till deposition across the ice base and how they may have co-evolved spatially and temporally during glacial cycles and with changing ice velocities. The evolution of ice sheets beds from 'soft' to 'mixed' and eventually 'hard' beds as antecedent sediment covers are progressively stripped off is of special interest.

Bedforms analogous to those on glacially-streamlined surfaces occur below the base of landslides and on faults, and also as micro-forms on man-made wearing surfaces; this points to the need for a common approach to quantitative modeling of all types of streamlined forms produced by erodent layers.

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