

Clark C.D., Hughes A.L.C., Greenwood S.L., Spagnolo M., Ng F.S.L.

**Size and shape characteristics of drumlins, derived from a large sample, and associated scaling laws**

(2009) *Quaternary Science Reviews*, 28 (7-8), pp. 677-692.

Abstract

Ice sheets flowing across a sedimentary bed usually produce a landscape of blister-like landforms streamlined in the direction of the ice flow and with each bump of the order of 102 to 103 m in length and 101 m in relief. Such landforms, known as drumlins, have mystified investigators for over a hundred years. A satisfactory explanation for their formation, and thus an appreciation of their glaciological significance, has remained elusive. A recent advance has been in numerical modelling of the land-forming process. In anticipation of future modelling endeavours, this paper is motivated by the requirement for robust data on drumlin size and shape for model testing. From a systematic programme of drumlin mapping from digital elevation models and satellite images of Britain and Ireland, we used a geographic information system to compile a range of statistics on length  $L$ , width  $W$ , and elongation ratio  $E$  (where  $E = L/W$ ) for a large sample. Mean  $L$ , is found to be 629 m ( $n = 58,983$ ), mean  $W$  is 209 m and mean  $E$  is 2.9 ( $n = 37,043$ ). Most drumlins are between 250 and 1000 metres in length; between 120 and 300 metres in width; and between 1.7 and 4.1 times as long as they are wide. Analysis of such data and plots of drumlin width against length reveals some new insights. All frequency distributions are unimodal from which we infer that the geomorphological label of 'drumlin' is fair in that this is a true single population of landforms, rather than an amalgam of different landform types. Drumlin size shows a clear minimum bound of around 100 m (horizontal). Maybe drumlins are generated at many scales and this is the minimum, or this value may be an indication of the fundamental scale of bump generation ('proto-drumlins') prior to them growing and elongating. A relationship between drumlin width and length is found (with  $r^2 = 0.48$ ) and that is approximately  $W = 7 L^{1/2}$  when measured in metres. A surprising and sharply-defined line bounds the data cloud plotted in  $E$ - $W$ - $L$  space, and records a scale-dependent maximum elongation limit (approximated by  $E_{max} = L^{1/3}$ , when  $L$  measured in metres). For a given length, for some reason as yet unknown, drumlins do not exceed the elongation ratio defined by this scaling law. We also report and compare our statistics to an amalgamated sample (25,907 drumlins) of measures derived from around 50 published investigations. Any theory must be able to explain the drumlin statistics and fundamental scaling properties reported herein and they thus provide powerful tests for drumlin modelling. © 2008 Elsevier Ltd. All rights reserved.

Fowler A.C.

**Instability modelling of drumlin formation incorporating lee-side cavity growth**

(2009) *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 465 (2109), pp. 2681-2702.

Abstract

It is proposed that the formation of the subglacial bedforms known as drumlins occurs through an instability associated with the flow of ice over a wet deformable till. We pose a mathematical model that describes this instability, and we solve a simplified version of

the model numerically in order to establish the form of finite-amplitude two-dimensional waveforms. A feature of the solutions is that cavities frequently form downstream of the bedforms; we allow the model to cater for this possibility and we provide an efficient numerical method to solve the resulting free boundary problem.

King E.C., Hindmarsh R.C.A., Stokes C.R.

**Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream .**

(2009) *Nature Geoscience*, 2 (8), pp. 585-588.

Abstract

Most discharge from large ice sheets takes place through fast-flowing ice streams and their speed is strongly modulated by interactions between the ice and the underlying sediments. Seismic surveys and investigations through boreholes have revealed a spatial association between fast ice flow and saturated deformable sediments. Nevertheless, our knowledge of the morphology of the interface between ice and sediments is still limited, resulting in only rudimentary understanding of the basal boundary conditions beneath ice streams and the generation of subglacial bedforms. Here we present radar data from the bed of a West Antarctic ice stream that reveal the presence of mega-scale glacial lineations. We combine these data with previously published seismic data and show that these lineations develop in areas of dilatant deforming till and are part of a dynamic sedimentary system that undergoes significant change by erosion and deposition on decadal timescales. We find that the mega-scale glacial lineations are indistinguishable from those found on beds of palaeo-ice streams, providing conclusive evidence for the hypothesis that highly elongate bedforms are a characteristic of fast-flow regions in ice sheets.

Dunlop P., Clark C.D., Hindmarsh R.C.A.

**Bed ribbing instability explanation: Testing a numerical model of Ribbed moraine formation arising from couple flow of ice and subglacial sediment**

(2008) *Journal of Geophysical Research F: Earth Surface*, 113 (3), art. no. F03005, .

Abstract

Ribbed moraines are large (up to 16 km long) ridges of sediment produced transverse to ice flow direction that formed widely beneath palaeo-ice sheets. Since ice sheet stability is sensitive to conditions operating at the bed, an understanding of ribbed moraine genesis will provide critical information on ice sheet dynamics. Currently, there is no consensus on ribbed moraine formation and various competing hypotheses have been presented to account for their genesis. Only one of these theories has been developed into a physically based numerical model that quantitatively describes ribbed moraine formation. This theory, known as the Bed Ribbing Instability Explanation (BRIE), argues that ribbed moraines are produced by a naturally arising instability in the coupled flow of ice and till. BRIE demonstrates that transverse subglacial ridges (i.e., ribbed moraine) spontaneously grow under certain parameter combinations, and it predicts their wavelength (spacing between ridges). The model represents a significant advance because it is the first time a theory of subglacial bedform generation has been developed to make quantitative

predictions which can be formally tested. This paper discusses the types of tests that are currently possible and reports the results from the first testing of BRIE. This analysis centers on the ability of BRIE to predict the primary characteristics of ribbed moraine, which are patterning and wavelength. Results show that BRIE successfully predicts the correct ribbed moraine pattern and appropriate wavelengths. The tests fail to falsify the model, and it is concluded that BRIE remains a viable explanation of ribbed moraine formation. Copyright 2008 by the American Geophysical Union.

Robinson M., Fowler A.C., Alexander A.J., O'Brien S.B.G.

### **Waves in guinness**

(2008) *Physics of Fluids*, 20 (6), art. no. 067101, .

#### Abstract

We describe a simple model of a bubbly two-phase flow which is able to explain why waves propagate downward when a pint of Guinness is poured, and also how the waves are generated. Our theory involves a physically based regularization of the basic equations of the two-phase flow, using interphasic pressure difference and virtual mass terms, together with bulk or eddy viscosity terms. We show that waves can occur through an instability analogous to that which forms roll waves in inclined fluid flows, and we provide a description of the form of these waves, and compare them to observations. Our theory provides a platform for the description of waves in more general bubbly two-phase flows, and the way in which the flow breaks down to form slug flow. © 2008 American Institute of Physics.

Stokes C.R., Lian O.B., Tulaczyk S., Clark C.D.

### **Superimposition of ribbed moraines on a palaeo-ice-stream bed: Implications for ice stream dynamics and shutdown**

(2008) *Earth Surface Processes and Landforms*, 33 (4), pp. 593-609.

#### Abstract

The sediments and landforms preserved on palaeo-ice-stream beds can provide important information about their subglacial conditions and flow mechanisms, and the processes accompanying their shutdown. In this paper, detailed observations of an intriguing subglacial landform assemblage of ribbed moraines superimposed on glacial lineations on the Dubawnt Lake Ice Stream bed (north-west Canadian Shield) are presented, including their morphometry, internal structure (from ground penetrating radar (GPR) surveys and from glaciogeological analysis) and sedimentological characteristics (from sediment architecture and lithofacies analysis). The observations suggest an abrupt change in ice dynamics that correlates with two phases of glacial landform development. This hypothesis is based on evidence from a deformed lodgement till, which subsequently underwent brittle deformation and developed prominent thrust (shear) structures and tension fractures. Tension fractures are observed in a sediment exposure and thrust structures are observed in GPR surveys, where they occur most prominently in the ribbed moraine ridge crests. The presence of the fractures, and their association with a population of clasts in the till that are orientated with their a-axes transverse to the inferred ice flow direction, suggests a compressional flow regime. It is therefore inferred that the glacial lineations were formed under an extensional flow regime during ice

stream activity, but that at some point patches of till under the ice stream stiffened through dewatering. The subsequent increase in basal shear stress resulted in compressional flow and the development of subglacial thrusting and the building of ribbed moraines. We therefore suggest that ribbed moraines may form in areas of compressional flow under ice streams, i.e. sticky spots, and/or at the transition between slow and fast ice flow along parts of an ice stream. The general absence of ribbed moraines on most other palaeo-ice-stream beds suggests that either these ice streams continued operating during deglaciation or processes other than the development of localized compressional flow (sticky spots) led to their shutdown (e.g. ice depletion). Copyright © 2008 John Wiley & Sons, Ltd.

Dunlop P., Clark C.D.

**The morphological characteristics of ribbed moraine**

(2006) *Quaternary Science Reviews*, 25 (13-14), pp. 1668-1691.

Abstract

Ribbed (Rogen) moraines are large subglacially formed transverse ridges that cover extensive areas of the former Laurentide, Scandinavian and Irish ice sheets. Given their ubiquitous and conspicuous nature, it is surprising that their characteristics are poorly understood. To date, most ribbed moraine studies have been spatially restricted and rely on small sample sizes. Thus, published accounts of their characteristics are most likely unrepresentative of ribbed moraines generally. This study addresses this deficit by producing the first representative data set on ribbed moraine size, shape, pattern and distribution and we describe their spatial characteristics. Various remote sensing and GIS techniques were used to map ribbed moraines over a combined area of 81,000 km<sup>2</sup> in Canada, Ireland and Sweden producing a database of just over 33,000 individual landforms. In all, 25,082 ridges were mapped in two areas in central and northern Québec (the Lac Naococane and River Kaniapiskau regions), 5637 in the Lake Rogen area of central Sweden and 2500 in north central Ireland. In comparison against the published accounts of ribbed moraine we demonstrate that some widely held assertions are inaccurate or untrue, and we show that ribbed moraine morphological characteristics are more complex than has been hitherto reported. Our data reveals they exist over a larger scale range than was previously stated. This study concludes by presenting a list of ribbed moraine characteristics and argues that formational hypotheses must account for these if they are to remain valid explanations of ribbed moraine genesis. © 2006 Elsevier Ltd. All rights reserved.

Stokes C.R., Clark C.D., Winsborrow C.M.

**Subglacial bedform evidence for a major palaeo-ice stream and its retreat phases in Amundsen Gulf, Canadian Arctic Archipelago**

(2006) *Journal of Quaternary Science*, 21 (4), pp. 399-412.

Abstract

Ascertaining the location of palaeo-ice streams is crucial in order to produce accurate reconstructions of palaeo-ice sheets and examine interactions with the ocean-climate system. This paper reports evidence for a major ice stream in Amundsen Gulf, Canadian Arctic Archipelago. Mapping from satellite imagery (Landsat ETM+) and digital elevation models, including bathymetric data, is used to reconstruct flow-patterns on

southwestern Victoria Island and the adjacent mainland (Nunavut and Northwest Territories). Several flow-sets indicative of ice streaming are found feeding into the marine trough and cross-cutting relationships between these flow-sets (and utilising previously published radiocarbon dates) reveal several phases of ice stream activity centred in Amundsen Gulf and Dolphin and Union Strait. A large erosional footprint on the continental shelf indicates that the ice stream (ca. 1000 km long and ca. 150 km wide) filled Amundsen Gulf, probably at the Last Glacial Maximum. Subsequent to this, the ice stream reorganised as the margin retreated back along the marine trough, eventually splitting into two separate low-gradient lobes in Prince Albert Sound and Dolphin and Union Strait. The location of this major ice stream holds important implications for ice sheet-ocean interactions and specifically, the development of Arctic Ocean ice shelves and the delivery of icebergs into the western Arctic Ocean during the late Pleistocene. Copyright © 2006 John Wiley & Sons, Ltd.

Smith M.J., Clark C.D.

**Methods for the visualization of digital elevation models for landform mapping**

(2005) *Earth Surface Processes and Landforms*, 30 (7), pp. 885-900.

Abstract

Digital elevation models (DEMs) are increasingly used for landform mapping, particularly with the growing availability of national and global datasets. In this paper we describe a variety of techniques that can visualize a DEM. We then compare five techniques to ascertain which performs the most complete and unbiased visualization. We assess the visualization techniques by comparing landforms mapped from them against a detailed morphological map (derived from mapping of multi-azimuth relief-shaded DEMs cross-checked with stereo aerial photographs). Results show that no single visualization method provides complete and unbiased mapping. The relief-shaded visualizations are particularly prone to azimuth biasing, although they can highlight subtle landforms. We recommend curvature visualization for initial mapping as this provides a non-illuminated (and therefore unbiased) image. Initial mapping can then be supplemented with data from relief-shaded visualizations. Copyright © 2005 John Wiley & Sons, Ltd.

Clark C.D., Tulaczyk S.M., Stokes C.R., Canals M.

**A groove-ploughing theory for the production of mega-scale glacial lineations, and implications for ice-stream mechanics**

(2003) *Journal of Glaciology*, 49 (165), pp. 240-256.

Abstract

Mega-scale glacial lineations (MSGs) are longitudinally aligned corrugations (ridge-groove structures 6-100 km long) in sediment produced subglacially. They are indicators of fast flow and a common signature of ice-stream beds. We develop a qualitative theory that accounts for their formation, and use numerical modelling, and observations of ice-stream beds to provide supporting evidence. Ice in contact with a rough (scale of 10-103 m) bedrock surface will mimic the form of the bed. Because of flow acceleration and convergence in ice-stream onset zones, the ice-base roughness elements experience transverse strain, transforming them from irregular bumps into longitudinally aligned

keels of ice protruding downwards. Where such keels slide across a soft sedimentary bed, they plough through the sediments, carving elongate grooves, and deforming material up into intervening ridges. This explains MSGLs and has important implications for ice-stream mechanics. Groove ploughing provides the means to acquire new lubricating sediment and to transport large volumes of it downstream. Keels may provide basal drag in the force budget of ice streams, thereby playing a role in flow regulation and stability. We speculate that groove ploughing permits significant ice-stream widening, thus facilitating high-magnitude ice discharge.

Stokes C.R., Clark C.D.

**Are long subglacial bedforms indicative of fast ice flow?**

(2002) *Boreas*, 31 (3), pp. 239-249.

Abstract

It has been suggested that extremely long subglacial bedforms (e.g. attenuated drumlins and mega-scale glacial lineations) record former areas of fast-flowing ice and that bedform elongation ratio is a useful proxy for ice velocity. Despite the availability of much data pertaining to the measurement and analysis of subglacial bedforms, these assumptions have rarely been explicitly addressed in detail. In this paper, we demonstrate that long subglacial bedforms (length:width ratios  $\approx 10:1$ ) are indicative of fast ice flow. Using satellite imagery, we mapped over 8000 lineaments associated with a highly convergent flow pattern near Dubawnt Lake, District of Keewatin, Canada. This flow pattern is unusual in that it displays a large zone of convergence feeding into a main 'trunk' and then diverging towards the inferred ice margin. The 'bottleneck' pattern is taken to record an increase and subsequent decrease in ice velocity and we analysed transverse and longitudinal variations in bedform morphometry. The main trunk of the flow pattern (down-ice of the convergent zone) is characterized by mega-scale glacial lineations of great length (up to 13 km) and high elongation ratios (up to 43:1). The down-ice variations in elongation ratio reflect exactly what we would expect from a terrestrial ice stream whose velocity increases in the onset zone passes through a maximum in the main trunk and slows down as the ice diverges at the terminus. It is suggested that any unifying theory of drumlin formation must be able to account for the association between long subglacial bedforms and fast ice flow, although it is not assumed that fast ice flow always produces attenuated bedforms. A further implication of this work is that many more ice streams may be identified on the basis of attenuated subglacial bedforms, radically altering our views on the flow dynamics of former ice sheets.

Tulaczyk S.M., Scherer R.P., Clark C.D.

**A ploughing model for the origin of weak tills beneath ice streams: A qualitative treatment**

(2001) *Quaternary International*, 86, pp. 59-70.

Abstract

Glaciological studies of West Antarctic ice streams have shown that weak sub-ice-stream tills provide the basal lubrication that makes fast ice streaming possible under low driving

stresses. Given the significant current interest in time-dependent ice stream behavior, there is a clear need for a conceptual model of weak sub-ice-stream tills that treats in a simple, but physically correct, way the coupling between evolution of till properties and ice stream dynamics. As a possible alternative to the previous, viscous-bed model, we propose a ploughing model that is consistent with the experimentally determined Coulomb-plastic rheology of sub-ice-stream till. In the ploughing model, the till is a several-meters-thick layer of sedimentary material that is disturbed and transported by ploughing that occurs during sliding of a bumpy ice base. The thickness of the till layer is determined in the ploughing model by the amplitude of the largest roughness elements ("ice keels"). There is no direct proof for the existence of ice bumps and ice keels beneath the modern West Antarctic ice streams but bedforms (e.g. megalineations and bundle structures) left behind by Pleistocene ice streams strongly support our assumption that an ice stream base is irregular. Generation of new till material occurs when ice keels protrude through the existing till layer and erode the top of the sub-till preglacial sediments. Based on a single tethered stake measurement of Engelhardt and Kamb (J. Glaciol. 44 (1998) 223) made at the UpB camp, Ice Stream B, West Antarctica (Fig. 1), we estimate that the till flux due to sliding with ploughing is there  $< 88 \text{ m}^3 \text{ yr}^{-1}$  per meter width. To balance the estimated till flux in the UpB area, substrata erosion by ice keels would have to take place at a high, but not unreasonable, non-dimensional rate of  $< 1.7 \times 10^{-4}$  (assuming 1% contact area). In the case of the West Antarctic ice streams, erosion of sub-till materials by ice keels may be particularly fast and unimpeded because these ice streams are overriding unlithified preglacial (Tertiary) sediments. The most significant implication of the proposed ploughing model is that it permits treating basal resistance to ice motion as being velocity independent (plastic till rheology) while allowing subglacial transport of till as in the viscous-bed model. Models of ice streams with a plastic bed exhibit a greater potential for unstable behavior than models of ice streams with viscous beds. © 2001 Elsevier Science Ltd and INQUA. All rights reserved.

Clark C.D., Meehan R.T.

**Subglacial bedform geomorphology of the Irish Ice Sheet reveals major configuration changes during growth and decay**

(2001) Journal of Quaternary Science, 16 (5), pp. 483-496.

Abstract

The belated realisation that ribbed (Rogen) moraines form such an integral part of Irish geomorphology, and the piecemeal approach to previous drumlin mapping, is probably responsible for the highly contrasting views of palaeoflow patterns of the Irish Ice Sheet. Using a high resolution (25 m) digital elevation model we present morphological maps of a large part (100 km<sup>2</sup>— 100 km) of the so-called 'Drumlin Belt' of north central Ireland. The landforms comprise mostly ribbed moraine much larger than found elsewhere (up to 16 km in length), which in places are superimposed on each other. Contrary to most prior assessments we find the bedform record to contain numerous and overlapping episodes of bed formation (ribbed moraine, drumlins and crag-and-tails) that provide a palimpsest record of changing flow geometries. These demonstrate an ice sheet with a centre of mass and flow geometry that changed during growth and decay. Using distinctive flow patterns

and relative age relationships between them we reconstruct ice sheet evolution into four phases during a single glacial cycle. In phase 1 (early in the glacial cycle), Scottish and local ice coalesced to form a northeast-centred Irish Ice Sheet. As it grew its centre of mass migrated southwards, culminating in a major N-S divide positioned down the east of Ireland (phase 2, ca. Last Glacial Maximum). During retreat, the centre of mass migrated at least 120 km northwards and became established in northwest Ireland and at this point a dramatic bedforming event produced one of the world's largest and most contiguous ribbed moraine fields (phase 3). Final deglaciation is thought to be by fragmentation into many topographically controlled minor ice-caps (phase 4). Rather than any dramatic or unexpected behaviour, the reconstructed phases indicate a relatively predictable pattern of ice sheet growth and decay with changes in centres of mass, and does not require major readvances or ice-stream events. Copyright © 2001 John Wiley & Sons, Ltd.

Clark C.D.

**Glaciodynamic context of subglacial bedform generation and preservation**

(1999) *Annals of Glaciology*, 28, pp. 23-32.

Abstract

Subglacially-produced drift lineations provide spatially extensive evidence of ice flow that can be used to aid reconstructions of the evolution of former ice sheets. Such reconstructions, however, are highly sensitive to assumptions made about the glaciodynamic context of lineament generation; when during the glacial cycle and where within the ice sheet were they produced. A range of glaciodynamic contexts are explored which include: sheet-flow submarginally restricted; sheet-flow pervasive; sheet-flow patch; ice stream; and surge or re-advance. Examples of each are provided. The crux of deciphering the appropriate context is whether lineations were laid down time-transgressively or isochronously. It is proposed that spatial and morphometric characteristics of lineations, and their association with other landforms, can be used as objective criteria to help distinguish between these cases. A logically complete ice-sheet reconstruction must also account for the observed patches of older lineations and other relict surfaces and deposits that have survived erasure by subsequent ice flow. A range of potential preservation mechanisms are explored, including: cold-based ice; low basal-shear stresses; shallowing of the deforming layer; and basal uncoupling.

Hindmarsh R.C.A.

**Coupled ice-till dynamics and the seeding of drumlins and bedrock forms**

(1999) *Annals of Glaciology*, 28, pp. 221-230.

Abstract

The geomorphological effects of ice sliding over till, internal deformation of till and till sliding over bedrock are considered. Two questions are examined: (1) is the till-sheet flow unstable; i.e. is a layer of uniform thickness maintained or not, and (2) does the slip of till over bedrock cause amplification of relief of the bedrock? Such instabilities seem to be necessary to explain such features as drumlins and whaleback forms. It is found that the answer to (1) and (2) depends on the position of the system in a parameter space,



defined by the till rheology, and applied shear stress, the effective pressure at the ice-till interface, the thickness of ice and till and the wavelength of the instability. Two configurations are considered: one where the wavelength of the perturbation is much less than the ice-thickness, which is related to the classical Nye-Kamb solution for flow over bumps; and one where the wavelength is much greater than the ice thickness, where the mechanics are described by the shallow-ice approximation. In both cases, substantial areas of parameter space, where till-sheet and bedrock modes are unstable, are found. The conceptually related Smalley-Unwin bifurcation is re-examined. The physical mechanisms by which ice and till flows couple are examined. At very short wavelengths (~10 m), the ice is so rigid that it forces till waves to move at the ice velocity; while at long wavelengths (~1000 m), the flows become essentially uncoupled and till waves move at the kinematic velocity. At intermediate wavelengths (~100 m), high growth rates occur; this is postulated to be the scale of drumlin seeding.

Hindmarsh R.C.A.

**Drumlinization and drumlin-forming instabilities: Viscous till mechanisms**

(1998) *Journal of Glaciology*, 44 (147), pp. 293-314.

Abstract

Glacially induced flow naturally tends to thin and extended till cover through shock formation, even in the absence of longitudinal gradients in the applied stress. Thicker till cover has an increased effective pressure at its surface and base, a lower sliding velocity or deformation rate and above a critical thickness, a decrease in wave velocity with thickness, leading to reverse-facing shocks moving downstream. For sliding and for some rheologies of internal deformation, a decrease in sediment flux with thickness occurs, implying backward-moving kinematic waves and reverse-facing, reverse-moving shocks. Downstream-facing shocks are also formed which move upstream if the till is sliding and downstream if the till is deforming internally. Eventually, shocks coalesce, leaving an upstream-facing shock for sliding and a downstream-facing shock for internal deformation. It is observed that some drumlins have downstream blunt ends only. Fairly realistic three-dimensional drumlin shapes can be produced from symmetric sediment bodies and barchan shapes can be produced from linear forms perpendicular to the ice-sheet flow. The fact that viscous theories produce drumlinoid forms suggests that on this scale till behaves viscously and the lower length scale for drumlins represents the plastic/viscous transition scale.

Hindmarsh R.C.A.

**The stability of a viscous till sheet coupled with ice flow, considered at wavelengths less than the ice thickness**

(1998) *Journal of Glaciology*, 44 (147), pp. 285-292.

Abstract

A perturbation method is used to analyse the stability of a thin till layer overlain by a deep ice layer. Ice is modelled as a linearly viscous fluid, while the till viscosity has power-law dependence on stress and effective pressure. A linearized set of equations yields descriptions of the coupling of the ice flow with the sediment flow and reveals

parameter ranges where the till-perturbation amplitude can grow. This sheet-flow instability is an essential part of any theory of drumlin formation and shows that viscous models of till have the ability to explain typical deforming-bed features. This is of great significance for large-scale ice-sheet modelling.

Clark C.D., Wilson C.

**Spatial analysis of lineaments**

(1994) *Computers and Geosciences*, 20 (7-8), pp. 1237-1258.

Abstract

This paper describes a program that will perform some simple spatial analysis of lineaments, and which is useful particularly for lineaments that are arranged as parallel sets. The lineaments may be geological faults, drumlins, linear sand dunes, or any other phenomena that can be mapped as single line-elements. The outputs from the program are lineament lengths, orientations, parallel and perpendicular spacings, nearest-neighbor distances, and an assessment of how the spatial distribution of the lineaments compares to a purely random pattern. The technique was developed to support research on subglacially produced lineaments (drumlins, mega-lineations, etc.) which requires large amounts of quantitative information to be acquired to test a number of hypotheses. The programs are written in "C" and designed for use on UNIX platforms. They accept inputs of simple ASCII files that define the endpoint coordinates of each lineament. © 1994.

Clark C.D.

**Large-scale ice-moulding: a discussion of genesis and glaciological significance**

(1994) *Sedimentary Geology*, 91 (1-4), pp. 253-268.

Abstract

Landsat images reveal a previously unsuspected large-scale pattern of streamlining within drift which comprises a number of components. Drumlins and megaflutes form part of the pattern, but in addition there are two previously undocumented ice-moulded landform elements: streamlined lineations of much greater proportions, referred to as mega-scale glacial lineations, and a distinctive cross-cutting topology within the grain. Consideration of the genesis and glaciological significance of such landforms leads to a number of conclusions. It is suggested that mega-scale glacial lineations were formed under conditions of fast ice flow and their presence may thus record former locations of ice streams or surge events. Many lineations of varying scales display a pattern that reveals that they were not formed in sub-marginal positions. Extensive sets of lineations must have been formed approximately synchronously, thus indicating that lineation generation occurs over a wide range of glaciodynamic conditions, from sub-marginal positions to interior portions of ice sheets. Subglacial deformation of tills has been widely invoked to account for rapid glacier motion. Criteria for identifying such tills are restricted to structures viewed in cross-section, and it is thus hard to assess how widespread the processes of deformation may have been. Lineations provide a surface "marker" of structure that records subsequent deformation from other ice-flow events. It is argued that the palaeo-flow record including cross-cutting patterns provides the surface or plan expression of subglacial deformation. The degree of modification to pre-existing

lineations should permit the identification of zones favoured by deformation, and thus assist in an assessment of how pervasive deforming bed processes were in influencing ice sheet dynamics. © 1994.

Clark C.D.

**Mega-scale glacial lineations and cross-cutting ice-flow landforms**

(1993) *Earth Surface Processes & Landforms*, 18 (1), pp. 1-29.

Abstract

Landsat images reveal a previously unsuspected large-scale pattern of streamlining within drift that is assumed to reflect former phases of ice flow. Drumlins and megaflutes form part of the pattern, but in addition there are two previously undocumented ice-moulded landform elements: streamlined lineations of much greater proportions, referred to as mega-scale glacial lineations, and a distinctive cross-cutting topology within the grain. The ice-moulded landform assemblage is described and illustrated with reference to examples from Canada. The discovery of this pattern indicates the pervasive nature of subglacial deformation of sediment, and demands a radical re-interpretation of ice sheet dynamics. -from Author

Clark C.D.

**Remote sensing scales related to the frequency of natural variation: An example from paleo-ice-flow in Canada**

(1990) *IEEE Transactions on Geoscience and Remote Sensing*, 28 (4), pp. 503-508.

Abstract

The importance of matching remote sensing scales to the frequency of variation in nature is discussed and illustrated by reference to the author's work on the search for pattern amongst noise within the geomorphic imprint produced by the last North American Ice Sheet. Utilization of six scales of remote sensing in the mapping of ice-flow landforms has led to a radical new interpretation of the dynamics and behavior of the Laurentide Ice Sheet. It is shown that incomplete sampling of the frequencies of natural variation can lead to a misleading or incorrect interpretations. This has implications for remote sensing investigations of many other natural phenomena.

