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The instability theory of drumlin formation and its explanation of their varied composition and internal structure

Chris R. Stokes [a,*], Andrew C. Fowler [b,c], Chris D. Clark [d], Richard C.A. Hindmarsh [e], Matteo Spagnolo [f]

[a] *Department of Geography, Durham University, Durham DH1 3LE, UK*
[b] *MACSI, Department of Mathematics and Statistics, University of Limerick, Limerick, Ireland*
[c] *Oxford Centre for Industrial and Applied Mathematics (OCIAM), Mathematical Institute, 24-29 St. Giles', Oxford OX1 3LB, UK*
[d] *Department of Geography, University of Sheffield, Sheffield S10 2TN, UK*
[e] *British Antarctic Survey, Madingley Road, Cambridge CB3 0ET, UK*
[f] *School of Geosciences, University of Aberdeen, UK*

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ABSTRACT

Despite their importance in understanding glaciological processes and constraining large-scale flow patterns in palaeo-glaciology, there is little consensus as to how drumlins are formed. Attempts to solve the 'drumlin problem' often fail to address how they are created from an initially flat surface in the absence of obvious cores or obstacles. This is a key strength of the instability theory, which has been described in a suite of physically-based mathematical models and proposes that the coupled flow of ice and till causes spontaneous formation of relief in the till surface. Encouragingly, model predictions of bedform height and length are consistent with observations and, furthermore, the theory has been applied to a range of subglacial bedforms and not just drumlins. However, it has yet to confront the myriad observations relating to the composition and internal structure of drumlins and this could be seen as a major deficiency. This paper is a first attempt to assess whether the instability theory is compatible with the incredible diversity of sediments and structures found within drumlins. We summarise the underlying principles of the theory and then describe and attempt to explain the main types of drumlin composition (e.g. bedrock, till, glaciofluvial sediments, and combinations thereof). Contrary to a view which suggests that the presence of some sedimentary sequences (e.g. horizontally stratified cores) is inconsistent with the theory, we suggest that one would actually expect a diverse range of constituents depending on the inheritance of sediments that pre-date drumlin formation, the duration and variability of ice flow, and the balance between erosion and deposition (till continuity) at the ice–bed interface. We conclude that the instability theory is compatible with (and potentially strengthened by) what is known about drumlin composition and, as such, offers the most complete and promising solution to the drumlin problem to date.

1. Introduction

Drumlins are one of the most widely studied landforms on Earth, with >1300 contributions (papers, abstracts and theses) in the literature and >400 scientific papers since 1980 (Clark et al., 2009). Their importance stems from their relevance to both glaciology and palaeo-glaciology. In glaciology, they are important because they are formed at the ice–bed interface and may exert a modulating effect on ice flow (Schoof, 2002a). However, our understanding of the subglacial processes that occur at this interface is incomplete, largely because of the inaccessibility of this environment under extant glaciers and ice sheets, which limits our observations to geophysical surveys or borehole sampling that cover relatively small areas (e.g. Tulaczyk et al., 2000; King et al., 2007, 2009). Thus, investigation of drumlins on former ice sheet beds has the potential to uncover important new insights regarding the mechanisms and feedbacks that act to sustain and/or inhibit ice flow and, importantly, formulate and test models of subglacial processes at the ice–bed interface (e.g. Hindmarsh, 1998a,b, 1999; Fowler, 2000, 2009; Schoof, 2007a,b). Ultimately, the success of such models to account for drumlin formation will improve our ability to predict the rate at which ice and sediment is transported from continents to the oceans, with important implications for future ice sheet stability (e.g. Schoof, 2002a, 2004).

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* Corresponding author. Tel.: +44 0 191 334 1955; fax: +44 0191 334 1801.
E-mail address: c.r.stokes@durham.ac.uk (C.R. Stokes).

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In palaeo-glaciology, drumlins also record key information relating to ice sheet flow history, e.g. ice flow direction and changes through time (cf. Boulton and Clark, 1990; Clark, 1993; Kleman and Borgström, 1996; Kleman et al., 1997, 2006), and even ice velocity (cf. Hart, 1999; Stokes and Clark, 2002). Thus, they are a vital ingredient for glacial inversion techniques that use the geological record of former ice sheet beds to reconstruct their time-dependent behaviour (see Kleman and Borgström, 1996; Kleman et al., 2006). It could be argued, however, that their use is yet to fulfil its true potential. If, for example, we knew the specific conditions under which drumlins of different shapes and sizes developed (e.g. specific ranges of ice thickness, velocity, effective pressures, etc.), then their importance to palaeo-glaciology would be considerably magnified.

With the above considerations in mind, the quest for a physically-based model of drumlin formation takes on huge importance and yet, despite this, their origin remains enigmatic and controversial. Numerous hypotheses of drumlin formation have been espoused and include accretion around obstacles (e.g. Fairchild, 1929), dilatant till behaviour (e.g. Smalley and Unwin, 1968), catastrophic meltwater floods (e.g. Shaw, 1983), deformation of till around more competent cores (e.g. Boulton, 1987), lee-side cavity infillings (e.g. Dardis, 1985) and an instability at the ice–till interface (e.g. Hindmarsh, 1998a). As noted by Clark (2010), however, most ideas/hypotheses of drumlin formation fail to address how bumps (drumlins) are created from a flat surface in the absence of obvious obstacles or cores. This appears to be a critical aspect of the 'drumlin problem' because although some drumlins possess an obvious core (e.g. of bedrock or 'stiffer' material), there are numerous reports in the literature of those that do not (see reviews in Patterson and Hooke, 1995; Stokes et al., 2011). Furthermore, most of the ideas regarding drumlin genesis are restricted to qualitative descriptions/explanations and very few have progressed to physically-based mathematical models that are capable of making predictions that can be tested against observations.

One theory of drumlin formation that does address relief amplification from an initially featureless surface is the instability theory and, significantly, the last decade or so has seen it described in numerical models of ice flowing over a layer of deforming sediment (e.g. Hindmarsh, 1998a,b, 1999; Fowler, 2000, 2009, 2010a; Schoof, 2007a,b). It proposes that the coupled flow of ice and till causes the spontaneous formation of relief in the till surface, whereby local highs at the bed will accumulate till by deposition, and lows will be preferentially eroded. This leads to the creation of pattern and structure in the bed that is manifest in a wide range of features termed subglacial bedforms. Indeed, a further appeal of this theory is that it has the potential to provide a unifying explanation for the production of a continuum of subglacial bedforms (cf. Aario, 1977; Rose, 1987) and not only drumlins, having been applied to ribbed moraine (Dunlop et al., 2008; Chapwanya et al., 2011) and recently adapted to address the formation of mega-scale glacial lineations (Fowler, 2010b).

Although models of the instability theory are yet to generate fully three-dimensional drumlins (see Section 2.2), predictions of bedform height and length in two-dimensional treatments are consistent with observations (e.g. Fowler, 2000, 2009), which is encouraging (see discussion in Clark, 2010). Perhaps more serious, however, is that the theory has yet to confront the multitude of observations relating to the composition and internal structure of drumlins. This was recently highlighted by Hiemstra et al. (2011) who noted that "theoretical studies of flow instability have yet to provide a solution for the sedimentological and structural–architectural variability in drumlins as recorded in the field". For some, this might be viewed as a deficiency: Hart (2005: p. 194), for example, notes that "any model of drumlin formation needs to be related to the sedimentology and structural geology of the drumlins themselves" and Schoof (2007a) questions whether the instability theory can be reconciled with observations of drumlins with stratified cores of glaciofluvial material (e.g. Easterbrook, 1986; Sharpe, 1987). Indeed, the oft-cited complexity of drumlin composition (e.g. Menzies, 1979; Patterson and Hooke, 1995) has frequently been seen as a major obstacle for a unifying theory of their formation, although this pessimism may be misplaced (see Stokes et al., 2011).

Whilst the instability theory is principally concerned with the evolution of the ice–till interface, it is important that it can explain observed sedimentary sequences within drumlins (at least qualitatively, but with further progress one anticipates quantitatively). If it is unable to accommodate common sedimentary architectures that are produced or, more commonly, inherited and preserved in a drumlin, then its credibility is damaged. With this in mind, this paper is the first attempt to assess the compatibility of the instability theory of drumlin formation with observations of their composition and internal structure. The underlying principles of the theory are introduced and we then outline a new framework for considering the composition of drumlins, before summarising the main types of drumlin composition reported in the literature (cf. Menzies, 1979; Patterson and Hooke, 1995; Stokes et al., 2011). Given the conceptual basis of the instability theory, we then consider what kinds of sediments and structures might be expected to occur based on firm physical principles, i.e. we consider the formation of drumlins in its physical context and use what we know or can reasonably infer about this context to provide an explanation of what has been observed in the field.

2. The instability theory for drumlin formation

2.1. Underlying principles

A system can be described as 'unstable' when positive feedbacks act to amplify small disturbances, such that small 'natural' variations (perturbations) become larger. A simple illustration of this process can be seen on a flat sand surface (e.g. a beach) where a small perturbation (e.g. a subtle change in sand thickness) encourages local sediment accretion and the growth of a sand ripple. Such instabilities generally grow exponentially, at a rate dependent on wavelength, and tend to grow fastest at a preferred wavelength. This wavelength of maximum growth rate is determined by the physical operation of the system and, significantly, because one wavelength tends to emerge as dominant, the result is often a pattern of similarly sized and spaced ripples (bedforms) in a field. Such relief amplification from an unstable interface is considered a fundamental mechanism for creating bedforms/waveforms into recognisable patterns, e.g. dunes and ripples in aeolian and fluvial landscapes (e.g. Prigozhin, 1999; Fowler, 2011), which resemble subglacial bedforms, see Fig. 1. As noted, the regularity of relief amplification (i.e. the spacing of bedforms at a dominant wavelength) arises because an instability in the system determines that one wavelength will usually grow more quickly than others and that patterning will further develop from bedform interactions, e.g. migration, merging, lateral linking, and cannibalisation might push the system towards fewer, larger, more widely spaced bedforms (Kocurek et al., 2010).

Clark (2010) provides a detailed review of the development of ideas relating to the instability theory for drumlin formation, which can be traced back to the seminal work of Smalley and Unwin (1968), who argued that drumlins might be the product of the