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A case study in the New York Drumlin Field, an investigation using microsedimentology, resulting in the refinement of a theory of drumlin formation

John Menzies [a,*], Dale P. Hess [b], Jessey M. Rice [c], Kaleb G. Wagner [d], Edouard Ravier [e]

[a] Department of Earth Sciences, Brock University, St. Catharines L2S 3A1, ON, Canada
[b] Department of Earth and Environmental Sciences, University of Rochester, NY 14627, USA
[c] Department of Earth and Environmental Sciences, University of Waterloo, Waterloo N2L 3G1, ON, Canada
[d] Minnesota Geological Survey, 2642 University Ave. W., St. Paul 55114, MN, USA
[e] Départment de Geosciences, Université du Maine, Avenue Olivier Messiaen, 72085 Le Mans, France

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ABSTRACT

The formation of drumlins remains a major enigma. It is accepted that drumlins form under active temperate ice most likely within a soft sediment deforming bed at ephemeral 'sticky points'. These 'sticky points' likely lead to the causative mechanism around which sediment nucleation occurs. The critical question is under what conditions and where and how do 'sticky spots' form. A comparative investigation of a drumlin and mega-flute in the New York Drumlin Field, as a case study, demonstrates that rheological and sedimentological tills from these different forms are similar. It is not, therefore, rheological change alone that must account for drumlin shape and form but likely the advective subglacial basal sediment flux rate at the ice bed. The rate of sediment motion between the upper interface at the ice–sediment bed boundary, and the lower immobile sediment at depth is crucial. At the lower décollement between the mobile and immobile sediment units, within the deforming sediment package, proto-drumlin nucleation is likely to occur and develop into a streamlined form. The trigger mechanism for such a perturbation is a derivative of sediment rheology and sediment flux rate driven by the overlying ice stresses. Recent evidence from Antarctica lends credence to this new hypothesis that can be related to all drumlins formed under temperate, soft sediment deforming bed conditions.

1. Introduction

The formation of drumlins has long confounded the geological community as one of its most puzzling and unresolved problems. Despite decades of research, a definitive process of formation remains elusive (e.g., Charlesworth, 1957; Menzies, 1979a, b, 1984, 1987; Smalley, 1966; Boulton, 1987; Kleman and Glasser, 2007; Clark et al., 2009; Johnson et al., 2010; Hooke et al., 2013; Ó Cofaigh et al., 2013; Stokes et al., 2013a, b; Jónsson et al., 2014; Trommelen and Ross, 2014; Dowling et al., 2015; Möller and Murray, 2015). Using the New York Drumlin Field (NYDF) as a case study, this paper explores the hypothesis that, under polythermal subglacial multi-interface ice masses, construction of drumlins and flutes is possible with no pre-existing nucleation in place. However, the final form and form variance require an additional set of subglacial conditions to be incorporated into any hypothesis of formation before a general hypothesis of formation for drumlins and flutes can be established. It is argued that the key in this hypothesis must be the sedimentological and glaciodynamic conditions under which drumlins and flutes can form. By comparing the sediments found in a large ovoid drumlin and a long mega-flute in the NYDF, some elucidation of this problem may emerge, and a new revised hypothesis of drumlin formation is presented.

2. A case study — the New York Drumlin Field (NYDF)

Over the past decade, extensive investigations of the NYDF have taken place with sampling of drumlin sediments, flutes and inter-drumlin areas in terms of macro- and microsedimentological studies (Menzies and Woodward, 1993; Dreger, 1994; Robertson, 1994; Menzies et al., 1997; Menzies and Brand, 2007; Hess et al., 2008; Hess and Briner, 2009). The result of these works, coupled with previous studies, has led to a broad understanding of the NYDF in terms of drumlin form across the field, and variations in changing macrosedimentology within drumlins and flutes.

The NYDF (Fig. 1) exhibits a range of drumlin forms and associated bedform types (flutes) with a marked transition from large ovoid drumlins in the north to long thin megaflutes towards its southern ice margin (Muller and Cadwell, 1986; Ridky and Bindschadler, 1990; Stahman, 1992; Yang, 1992; Briner, 2007; Kerr and Eyles, 2007; Hess

* Corresponding author. Tel.: +1 9056885550; fax: +1 9056889020.
E-mail address: jmenzies@brocku.ca (J. Menzies).

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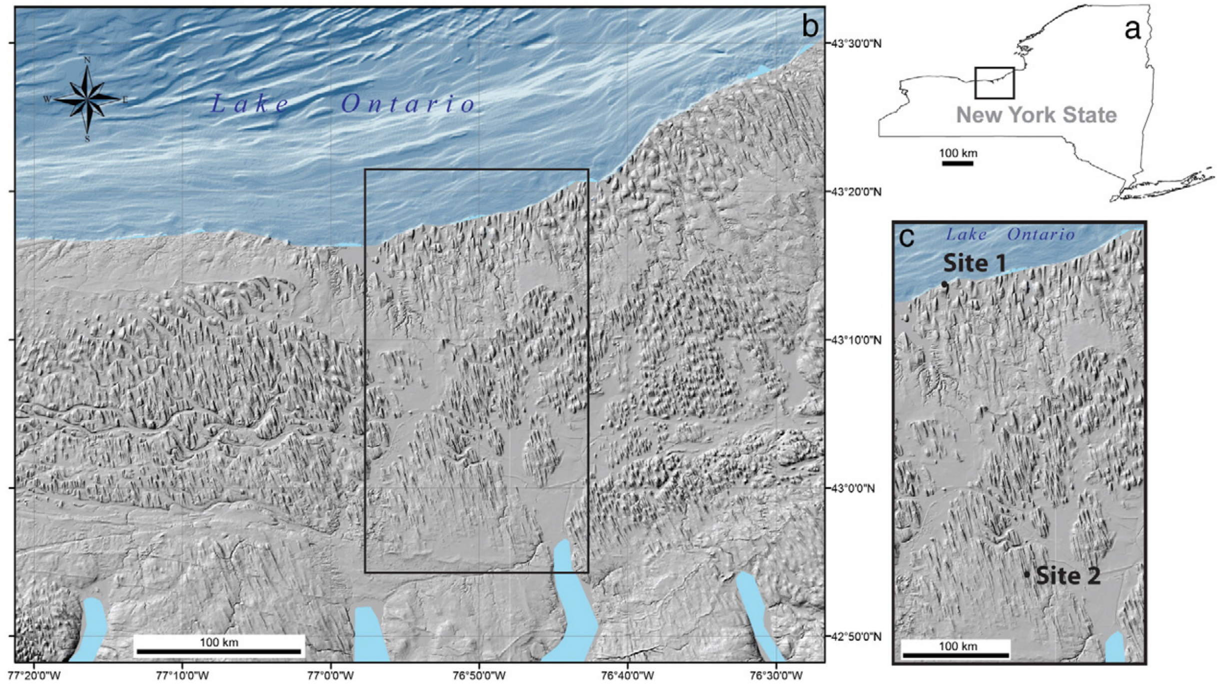

Fig. 1. Study area showing (a) map of New York State showing the location of the New York Drumlin Field; (b) enlarged view of the area highlighting the region of study; (c) central portion of the area showing a transition from ovoid drumlins in the north to attenuated bedforms in the south (after Hess and Briner, 2009). The map shows the sampling sites at the Chimney Bluffs drumlin (Site 1), and in a megaflute at West Tyre (Site 2).

and Briner, 2009). Stahman (1992) postulated that this drumlin and flute form variance may be indicative of repeated 'drumlin-forming' events as the ice sheet retreated and readvanced over this area of western New York State. Evidence to support this conclusion was found in a drumlin exposure where a marginal glaciofluvial delta was overrun and drumlinized (Menzies and Brand, 2007). Fleisher (2003) noted that towards the southernmost edge of the Laurentide Ice Sheet (LIS) in New York State a series of prograding deltas mark the edge of the retreating ice sheet. Others have suggested that as the LIS thinned towards its southern margin, basal stress levels may have altered such that flutes rather than drumlins evolved (Ross et al., 2011; Margold et al., 2014, 2015). Another hypothesis to explain the morphometric transition has been one of increasing basal ice velocity down-ice resulting in more elongate subglacial forms down the ice flow line as sediment supply thins (Kerr and Eyles, 2007). The hypothesized basal ice acceleration may be due to increasing soft sediment deformation, reduced effective stress levels and higher porewater, or accelerated flow due to the ice mass calving into ice-marginal lakes, or ice–bed decoupling or reducing supply of available sediment from up-ice or surging events by ice streams within the LIS (Stokes and Clark, 2002; Dowdeswell et al., 2004; King et al., 2009; Livingstone et al., 2012; Vreeland et al., 2015).

Sedimentologically the NYDF has been investigated almost continuously since the initial examinations by Martin (1901), Fairchild (1907, 1929), Slater (1926) and later workers (e.g., Admiraal, 1970; Miller, 1972; Calkin and Muller, 1992). In general, the NYDF drumlins are typically till-cored with occasional sand lenses occurring and, in places, sand intraclasts have been observed. In other places the drumlins contain substantial deltaic glaciofluvial units and glaciolacustrine beds. Fairchild (1929) and Slater (1926) extensively studied drumlin shore bluffs in the Sodus Bay area (on the southern shore of Lake Ontario) and commented on the glaciotectonic structures encountered and the often 'layering' or 'accretionary' appearance of tills in some exposures. However, few comparisons between drumlin tills within the NYFD have occurred nor between drumlin and flute sediments.

The study reported in the paper focused on macro- and microsedimentological internal investigations of (a) a large drumlin, with a length/width ratio of 2.3, sampled at Chimney Bluffs State Park (Site 1), and (b) a long low megaflute at West Tyre, with a length/width ratio of 11.3, located 33 km down the flow line from Chimney Bluffs (Site 2) (Hess, 2009) (Fig. 1c).

3. Methods

Sampling at the two sites was by both bulk and Kubiëna tin samples and each exposure was logged (Menzies et al., 1997; Hess, 2009) (Figs. 2, 3). Twenty-one samples at Chimney Bluffs and 5 at West Tyre were obtained towards the stoss end of both the drumlin and flute where access was permissible. The examples shown in Figs. 5, 6 are representative samples and serve to illustrate the microsedimentology at both sites. Sedimentological analyses were conducted on all samples while macrofabrics were taken from both sites (Figs. 5, 6). Standard particle size analyses were performed, Atterberg limits calculated in the laboratory, and vane shear tests conducted in the field (Fig. 4). Vane shear tests were conducted in hand dug pits down to 2.8 m in depth where tests were progressively completed at 1.0, 1.5, 2.0, 2.5 and 3.0 m in depth. Atterberg limits were completed on 10 samples per pit at the same site as the vane shear tests. Samples for microsedimentological analyses were taken for impregnation and thin section production resulted in 20 thin sections from Chimney Bluffs and 4 from West Tyre. A statement of caution needs to be added here in that in analyzing microshear angle great care had to be taken to cut the sediment as a thin section parallel to dip direction of the microfabric. Micromorphological sample preparation and thin section production were carried out following the steps and techniques outlined by Lee and Kemp (1993), van der Meer (1993), and Carr and Lee (1998). Analyses of thin sections were completed at low magnification (6.5–10×) in plain light using a Wild-Heerbrugg® M420 microscope, affixed with a Nikon® Digital sight DS-Fi1 digital imaging device. Samples were macroscopically examined and visible structures, range of grain size, and grain distribution were noted. Nikon® NIS-Br imaging software was then used to measure grain orientation, grain length, and sphericity of grains, and also to identify texturally different areas within the plasma. Images of slides were printed in high quality and a comprehensive