Supporting evidence from the New York drumlin field that elongate subglacial bedforms indicate fast ice flow

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Although drumlins and other subglacial bedforms are well-studied features, controls on their formation and morphometry have remained elusive. Of current interest is the hypothesis that elongate bedforms (length:width ratios ≥10) indicate fast ice flow, and perhaps the location of past ice streams. This hypothesis is explored by analysing drumlins from the New York State drumlin field. A subset of 548 drumlins between Oneida Lake and Lake Ontario was digitized using 10-m grid cell digital elevation data. Because bedform elongation is greatest along the axis of a reconstructed lobe and increases down flowline, elongate bedforms are best explained by fast ice flow. The swath of elongate bedforms between lakes Ontario and Oneida, the boundaries of which do not coincide with topography, may signify the location of an ice stream during deglaciation.

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Ice-sheet dynamics determine the response of ice sheets to climate change and are therefore important topics in today's rapidly changing world (Oppenheimer 1998; Zwally *et al.* 2002; De Angelis & Skvarca 2003). Our understanding of ice-sheet behaviour in part relies on reconstructions from former ice sheets, which rely largely on subglacial landforms to provide information on spatial and temporal patterns of palaeo-ice-sheet flow dynamics (Boulton & Clark 1990; Clark 1993; Kleman *et al.* 1997; Veillette *et al.* 1999), including the operation of fast ice flow or ice streams (Stokes & Clark 1999; Clark *et al.* 2003). The notion that elongate subglacial bedforms indicate fast ice flow (e.g. Chorely 1959) has gained support recently (Clark 1993, 1994), and Stokes & Clark (2002) suggest that the locations of fast ice flow and/or ice streams can be identified on the basis of elongate (length:width ratios ≥10) subglacial bedforms.

The southern margin of the Laurentide Ice Sheet was dynamically active with zones of fast ice flow. Large-scale topography (e.g. Patterson 1998), deformable sediment studies (e.g. Alley 1991; Clark 1991) and subglacial landform assemblages like drumlin fields (e.g. Hart 1999) point to spatially variable ice flow with zones of ice streaming. The well-studied drumlin field in New York State, USA (Fairchild 1905; Slater 1929; Muller 1974) is one such place that contains information on spatial patterns of basal ice flow. Although drumlins have been interpreted to have formed via a variety of mechanisms (e.g. Smalley & Unwin 1968; Boulton & Hindmarsh 1987; Shaw & Gilbert 1990; Boyce & Eyles 1991), those relating to subglacial sediment deformation are most widely accepted for New York drumlins (Menzies 1997; Clarke *et al.* 2005). Despite the fact that drumlins in New York represent a detailed pattern of subglacial ice flow, extracting information on basal ice-sheet dynamics has yet to be fully explored.

This study examines drumlins and megaflutes in the eastern portion of the New York drumlin field to test the hypothesis that elongate subglacial bedforms indicate fast ice flow. Unlike Francek's (1991) morphometric analysis that mainly focused on the influence of bedrock escarpments, or Stahman's (1992) and Hart's (1999) study of the Lake Cayuga megaflute fan in the central portion of the drumlin field, I measured elongation parameters of bedforms in the eastern portion of the field between lakes Ontario and Oneida (Fig. 1) using digital elevation data. The bedforms, which increase in elongation down flowline, most likely represent a zone of fast ice flow during the deglaciation of New York.

Methods

A subset of 548 bedforms between Oneida Lake and Lake Ontario was digitized using 1/3 Arc Second digital elevation data from the United States Geological Survey National Elevation Dataset (http://seamless.usgs.gov). A flowline was drawn parallel to bedform orientation (Fig. 1) along the centre of a reconstructed Oneida Lobe from which distance to bedform centre (in direction of bedform width) was measured using ImageJ (v. 1.32j; http://rsb.info.nih.gov/ij/). ImageJ was also used to measure bedform width and length, and elongation was subsequently calculated. The distance from the Lake Ontario shoreline along a flowline was measured on a subset ($n = 104$) of the most elongate bedforms. Bedforms were grouped into three zones

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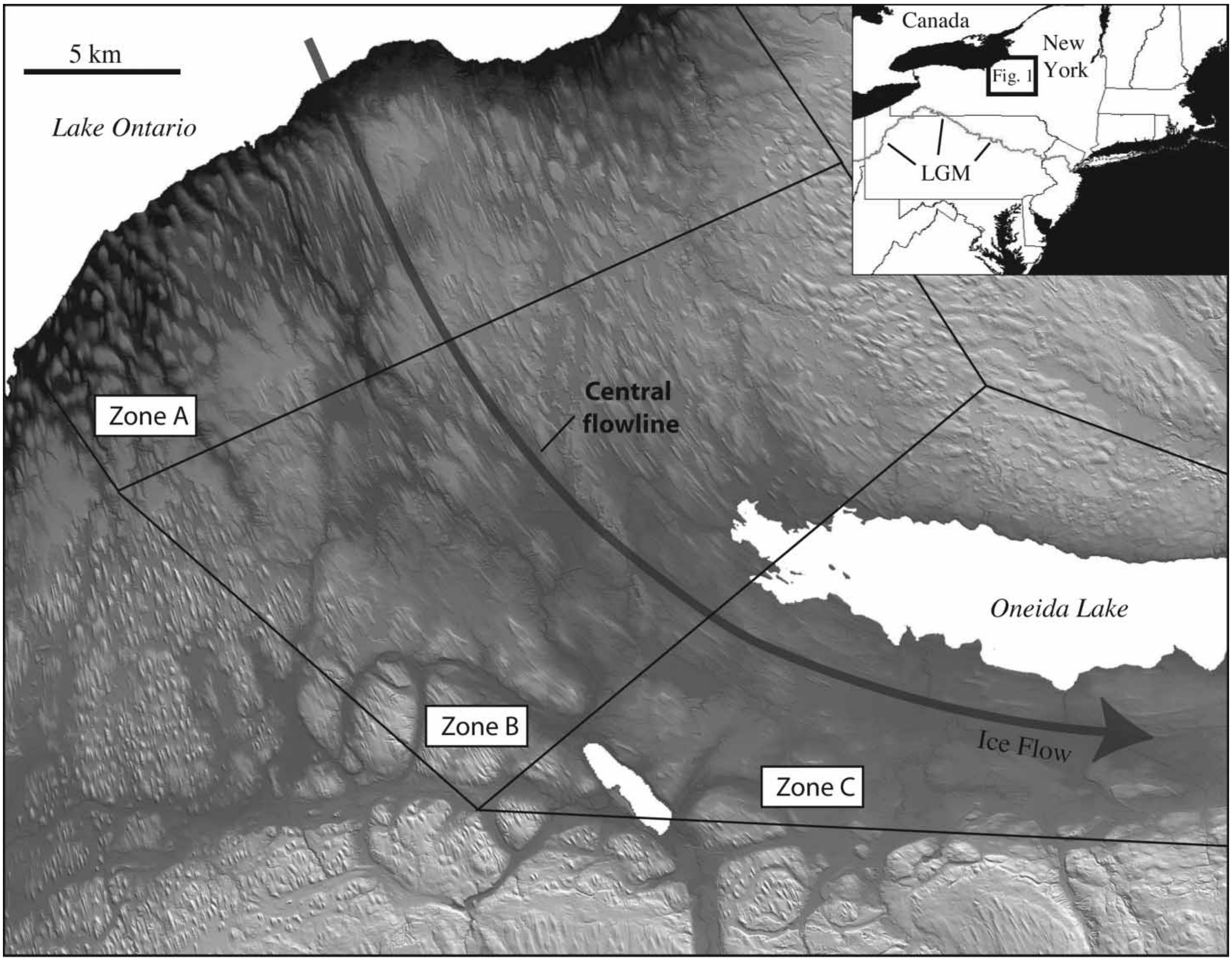

Fig. 1. Shaded-relief digital elevation map of the area between lakes Ontario and Oneida where drumlins were analysed. Study area was subdivided into three zones (A, B and C) outlined by black lines. The central flowline was drawn parallel to bedform orientations. Inset showing northeastern United States, New York and the Last Glacial Maximum (LGM) limit of the Laurentide Ice Sheet (from Dyke & Prest 1987).

between 0 and 18 km (zone A; $n = 269$), 18 and 48 km (zone B; $n = 201$) and 48 and 88 km (zone C; $n = 78$) down flowline (Fig. 1). From these data, plots were made of bedform elongation parallel and transverse to the former ice-flow direction.

Results

The length of the measured bedforms ranges between 580 and 6320 m, and elongation ratios range between 1.3 and 34.8 (Fig. 2). The majority of the bedforms classify as drumlins, although many classify as mega-flutes (Benn & Evans 1998: p. 425). Eighty-one bedforms (15%) have elongation ratios > 10, the ratio suggested by Stokes & Clark (1999) to indicate probable ice streaming. All three zones have a central area comprised of more elongate bedforms than to either side; I define the widths of these central areas as enclosing bedforms with maximum elongation ratios > 10 (Fig. 3). The average elongation of bedforms within the central areas increases down flowline from 8.1 ± 3.7 (zone A) to 10.5 ± 4.9 (zone B) to 12.8 ± 5.9 (zone C), whereas average elongation outside of the central areas remains roughly constant (3.9 ± 1.3 (A) to 4.3 ± 2.2 (B) to 3.5 ± 1.2 (C); Fig. 3). Finally, the widths of the central areas decrease down flowline from 18.3 (zone A) to 14.1 (zone B) to 8.6 km (zone C; Fig. 3).

Discussion

The curvilinear path of bedforms depicts the Oneida lobe flowing into the Oneida basin. There is evidence that this eastward-flowing lobe coalesced with a lobe flowing westward up the Mohawk River valley (Mohawk lobe) during early deglaciation of New York (18 to 16 kyr BP; Ridge *et al.* 1991). The coalescence of

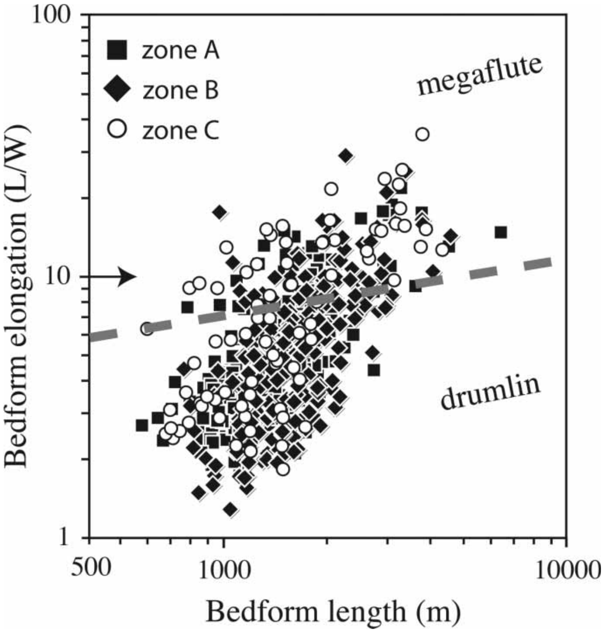

Fig. 2. Bedform elongation versus bedform length. Thick dashed line separates drumlins from megaflutes. Elongation ratios >10 are those hypothesized by Stokes & Clark (2001) to indicate fast ice flow or ice streaming.

these two lobes took place *c*. 35 km beyond the eastern shore of Oneida Lake. The Oneida lobe subsequently reached a similar extent when it deposited a portion of the Valley Heads moraine, a prominent ice-marginal feature that can be traced 100s of km (Muller & Calkin 1993). The bedforms studied herein were most recently shaped during this final advance of the Ontario lobe into the Oneida basin that took place between the deposition of the Valley Heads moraine *c*. 16 kyr BP (Muller & Cadwell 1986; Mullins & Hinchey 1989; Ridge *et al.* 1991; Muller & Calkin 1993) and the inception of Lake Iroquois *c*. 14.5 kyr BP (Muller & Prest 1985; Muller & Calkin 1993).

Several processes have been proposed that lead to elongated subglacial bedforms. Menzies *et al.* (1997) studied till microstructures of drumlins in the study area and concluded that the New York drumlins were formed via bed deformation during till emplacement. Boyce & Eyles (1991) found that bedform elongation decreases down a flowline on the north side of Lake Ontario, and suggested that duration of ice flow was a major factor leading to drumlin elongation. In contrast, the bedforms studied herein between lakes Oneida and Ontario become more elongated down flowline (Fig. 4); therefore, ice velocity, rather than ice-flow duration, may be a better explanation for the elongation of these particular bedforms. This hypothesis is also supported by the pattern of more

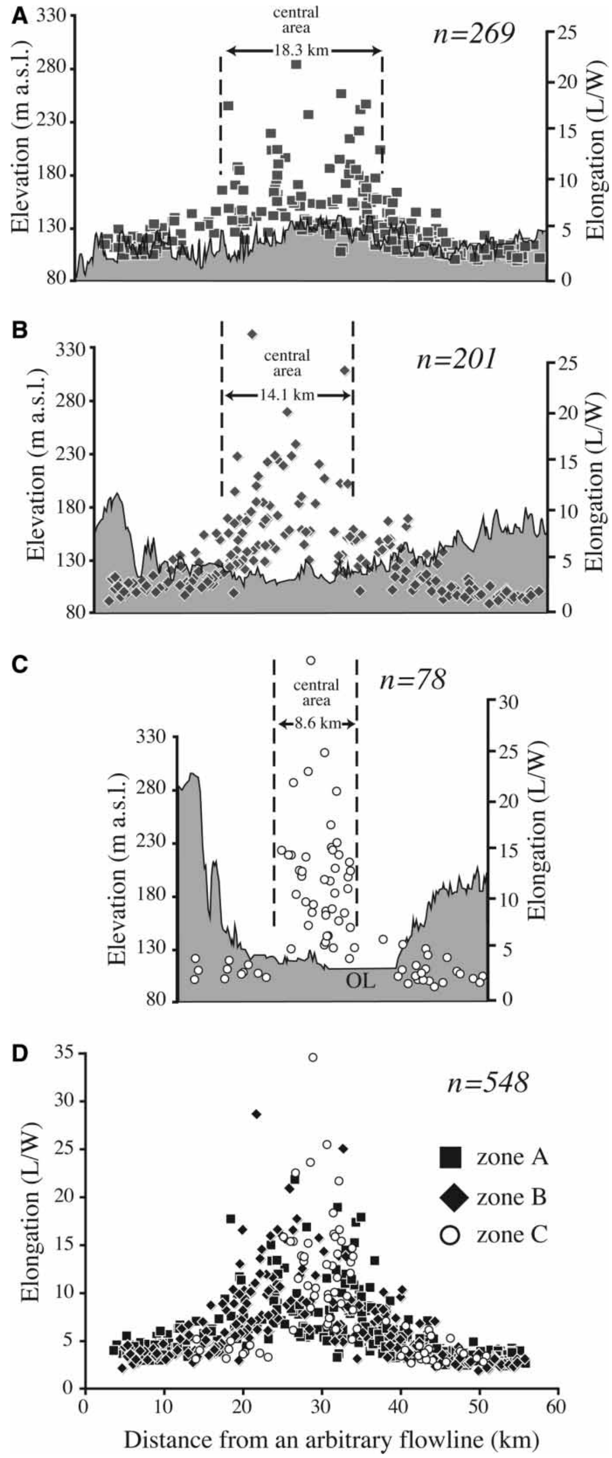

Fig. 3. Each of the study zones has a central area with bedform elongation ratios >10 bounded by areas on either side with elongation ratios <10. The width of these central zones decreases down the flowline from 18.3 to 14.1 to 8.6 km. Panels A through C correspond with zones A through C; their x-axis is shown on panel D, which shows all bedforms.

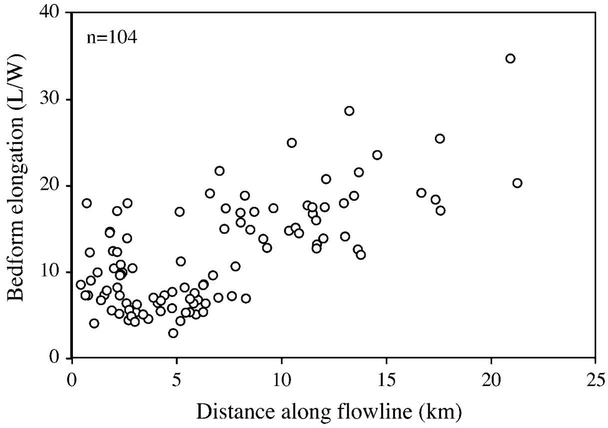

Fig. 4. Bedform elongation versus distance along the flowline shown in Fig. 1.

elongate bedforms along the axis of the reconstructed lobe, where ice would have been flowing fastest (cf. Hart 1999). Based on these two patterns of bedform elongation, velocity is the best explanation for elongating the bedforms in the study area.

Additional factors that control bedform elongation, such as substrate materials or post-depositional modification, also need to be considered. One possibility is that bedforms are more elongate where subglacial sediment has a lower shear strength and thus is more deformable. Indeed, the surficial deposits vary across the study area. For example, lacustrine silt and clay are widespread near the central axis of zones B and C, whereas variably textured till is the dominant surficial deposit closer to Lake Ontario and zone A (Muller & Cadwell 1986). If the lacustrine sediments were deposited by Lake Iroquois (Muller & Prest 1985), then they post-date bedform formation; however, pre-Iroquois lacustrine sediments may also have existed in this location, and may have served to lubricate the bed. An additional complicating factor is the erosion of bedforms by glacial Lake Iroquois, a large glacial lake in the Ontario basin that partially covered the New York drumlin field (e.g. Muller & Prest 1985). Drumlins that were near the former Lake Iroquois shoreline have been removed by wave action (e.g. Francek 1991). Bedforms below this elevation, although largely intact, have been partially buried and thus may appear narrower and shorter than they actually are. Although this generally would not affect bedform elongation ratios, their measured lengths may be underestimates.

The swath of elongate bedforms between lakes Ontario and Oneida likely represents a zone of fast ice flow during the deglaciation of New York. Although this lobe of the Laurentide Ice Sheet likely was funnelled by topography into the Oneida Basin, the sharp transition of highly elongate bedforms in the central swath of zone 3 (average elongation 12.8 ± 5.9) to bedforms on either side with much lower elongation ratios (3.5 ± 1.2) does not coincide with the valley walls (Fig. 3). This suggests that a zone of fast flowing ice may have existed directly adjacent to a zone of much slower moving ice, behaviour typical of ice streaming. Similarly, that a central swath of elongate bedforms exists in zone 1, with no constraining topography to either side, is also suggestive of streaming ice.

The notion that fast ice flow attenuates subglacial bedforms has been widely documented. Because remotely sensed data are being gathered at higher resolution, from above and below sea level, the quantification of bedform geometry is increasingly accessible. Several studies have suggested that elongate subglacial bedforms beneath the former Laurentide Ice Sheet represent areas of former ice streams (Dyke & Morris 1988; Clark 1993; Hart 1999; Stokes & Clark 1999, 2001, 2002). In particular, Hart (1999), building on Stahman (1992), analysed bedforms near Lake Cayuga (*c.* 10 km west of this study area) and found a similar pattern of increasing bedform elongation down a flowline and toward a central axis. Patterns of subglacial bedforms beneath the Fennoscandian Ice Sheet have also been associated with the locations of former ice streams (Kleman *et al.* 1997; Boulton *et al.* 2001; Jørgensen & Piotrowski 2003; Rattas & Piotrowski 2003; Sejrup *et al.* 2003; Landvik *et al.* 2005). In addition, elongate subglacial bedforms exist on the sea floor beyond contemporary ice streams in Antarctica (e.g. Canals *et al.* 2000; Anderson *et al.* 2001). Thus, the data presented here join a growing body of literature that supports a link between elongate drumlins/megaflutes and fast ice flow.

Conclusion

Despite our lack of a complete understanding of the depositional regime of subglacial bedforms, like drumlins, their orientation and elongation provide a wealth of information on past ice-sheet dynamics. Bedform variability recorded in the New York drumlin field provides insights about the dynamics and deglaciation style of the Laurentide Ice Sheet. Because bedform elongation increases down a flowline between lakes Ontario and Oneida and increases toward the axis of the reconstructed lobe, elongation is best explained by fast ice flow in this location. Thus, this study supports the hypothesis that the attenuated bedforms in the New York drumlin field indicate fast ice flow. The swath of elongate bedforms in the study area may signify the location of an ice stream during deglaciation, and attests to dynamic ice-sheet behaviour on deformable substrates.

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References

Alley, R. B. 1991: Deforming-bed origin for southern Laurentide till sheets. *Journal of Glaciology 37*, 67–76.

Anderson, J. B., Wellner, J. S., Lowe, A. L., Mosola, A. B. & Shipp, S. S. 2001: Footprint of the expanded West Antarctic Ice Sheet: Ice stream history and behavior. *Geological Society of America Today 10*, 1–9.

Benn, D. I. & Evans, D. J. A. 1998: *Glaciers and Glaciation*. 733 pp. Arnold, London.

Boulton, G. S. & Clark, C. D. 1990: A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations. *Nature 349*, 813–817.

Boulton, G. S. & Hindmarsh, R. C. A. 1987: Sediment deformation beneath glaciers: rheology and geologic consequences. *Journal of Geophysical Research 92*, 9059–9082.

Boulton, G. S., Dongelmans, P., Punkari, M. & Broadgate, M. 2001: Paleoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weischselian. *Quaternary Science Reviews 20*, 591–625.

Boyce, J. I. & Eyles, N. 1991: Drumlins carved by deforming till streams below the Laurentide ice sheet. *Geology 19*, 787–790.

Canals, M., Urgeles, R. & Calafat, A. M. 2000: Deep sea-floor evidence of past ice streams off the Antarctic Peninsula. *Geology 28*, 31–34.

Chorley, R. J. 1959: The shape of drumlins. *Journal of Glaciology 3*, 339–344.

Clark, C. D. 1993: Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surface Processes and Landforms 18*, 1–29.

Clark, C. D., Evans, D. J. A. & Piotrowski, J. A. 2003: Palaeo-ice streams: an introduction. *Boreas 32*, 1–3.

Clark, P. U. 1991: Striated clast pavements: products of deforming subglacial sediment? *Geology 19*, 530–533.

Clark, P. U. 1994: Unstable behavior of the Laurentide Ice Sheet over deforming sediment and its implications for climate change. *Quaternary Research 41*, 19–25.

Clarke, G. K. C., Leverington, D. W., Teller, J., Dyke, A. S. & Marshall, S. J. 2005: Fresh arguments against the Shaw megaflood hypothesis. A reply to comments by David Sharpe on 'Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event'. *Quaternary Science Reviews 24*, 1533–1541.

De Angelis, H. & Skvarca, P. 2003: Glacier surge after ice shelf collapse. *Science 299*, 1560–1562.

Dyke, A. S. & Morris, T. F. 1988: Drumlin fields, dispersal trains, and ice streams in Arctic Canada. *Canadian Geographer 32*, 86–90.

Dyke, A. S. & Prest, V. K. 1987: Late Wisconsin and Holocene retreat of the Laurentide Ice Sheet. *Geological Survey of Canada*, *Map 1702A, scale 1:5,000,000.*

Fairchild, H. L. 1905: New York drumlins. *Geological Society of America Bulletin 16*, 576.

Francek, M. A. 1991: A spatial perspective on the New York drumlin field. *Physical Geography 12*, 1–18.

Hart, J. K. 1999: Identifying fast ice flow from landform assemblages in the geological record: a discussion. *Annals of Glaciology 28*, 59–66.

Jørgensen, F. & Piotrowski, J. A. 2003: Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation. *Boreas 32*, 242–255.

Kleman, J., Hättestrand, C., Borgström, I. & Stroeven, A. 1997: Fennoscandian paleoglaciology reconstructed using a glacial geological inversion model. *Journal of Glaciology 43*, 283–299.

Landvik, J. Y., Ingólfsson, Ó., Mienert, J., Lehman, S. J., Solheim, A., Elverhøi, A. & Ottesen, D. 2005: Rethinking Late Weichselian ice sheet dynamics in coastal NW Svalbard. *Boreas 34*, 7–24.

Menzies, J., Zaniewski, K. & Dreger, D. 1997: Evidence, from microstructures, of deformable bed conditions within drumlins, Chimney Bluffs, New York State. *Sedimentary Geology 111*, 161–175.

Muller, E. H. 1974: Origins of drumlins. *In* Coates, D. R. (ed.): *Glacial Geomorphology*, 187–204. State University of New York, Binghamton.

Muller, E. H. & Cadwell, D. H. 1986: Surficial geologic map of New York–Finger Lakes sheet: Albany, New York State Museum. *Geological Survey Map and Chart Series 40*, *1 sheet, scale 1:250,000.*

Muller, E. H. & Calkin, P. E. 1993: Timing of Pleistocene events in New York State. *Canadian Journal of Earth Science 30*, 1829–1845.

Muller, E. H. & Prest, V. K. 1985: Glacial lakes in the Ontario Basin. *In* Karrow, P. F. & Calkin, P. E. (eds.): *Quaternary Evolution of the Great Lakes. Geological Association of Canada Special Paper 30*, 213–229.

Mullins, H. T. & Hinchey, E. J. 1989: Erosion and infill of New York Finger Lakes: implications for the Laurentide Ice Sheet deglaciation. *Geology 17*, 622–625.

Oppenheimer, M. 1998: Global warming and the stability of the West Antarctic Ice Sheet. *Nature 393*, 325–332.

Patterson, C. J. 1998: Laurentide glacial landscapes: the role of ice streams. *Geology 26*, 643–646.

Rattas, M. & Piotrowski, J. A. 2003: Influence of bedrock permeability and till grain size on the formation of the Saadjärve drumlin field, Estonia, under an east-Baltic Weichselian ice stream. *Boreas 32*, 167–177.

Ridge, J. C., Franzi, D. A. & Muller, E. H. 1991: Late Wisconsin, pre-Valley Heads glaciation in the western Mohawk valley, central New York, and its regional implications. *Geological Society of America Bulletin 103*, 1032–1048.

Sejrup, H. P., Larsen, E., Haflidason, H., Berstad, I. M., Hjelstuen, B. O., Jonsdottir, H., King, E. L., Landvik, J., Longva, O., Nygard, A., Ottesen, D., Raunholm, S., Rise, L. & Stalsberg, K. 2003: Configuration, history, and impact of the Norwegian Channel Ice Stream. *Boreas 32*, 18–36.

Shaw, J. & Gilbert, R. 1990: Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. *Geology 18*, 1169–1172.

Slater, G. 1929: The structure of drumlins on the south shore of Lake Ontario. *New York State Museum Bulletin 281*, 3–19.

Smalley, I. J. & Unwin, D. J. 1968: Formation and shape of drumlins and their distribution and orientation in drumlin fields. *Journal of Glaciology 7*, 377–390.

Stahman, D. A. 1992: *Composition and Shape of Fluted and Equant Drumlins in North Central New York Drumlin Field*. M.Sc. thesis, University of Lehigh, 60 pp.

Stokes, C. R. & Clark, C. D. 1999: Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology 28*, 67–74.

Stokes, C. R. & Clark, C. D. 2001: Paleo-ice streams. *Quaternary Science Reviews 20*, 1437–1457.

Stokes, C. R. & Clark, C. D. 2002: Are long subglacial bedforms indicative of fast ice flow? *Boreas 31*, 239–249.

Veillette, J. J., Dyke, A. S. & Roy, M. 1999: Ice-flow evolution of the Labrador sector of the Laurentide Ice Sheet: a review, with new evidence from northern Quebec. *Quaternary Science Reviews 18*, 993–1019.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J. & Steffen, K. 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science 297*, 218–222.