

Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset

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ABSTRACT: Mega-scale glacial lineations (MSGs) are a characteristic landform on ice stream beds. Solving the puzzle of their formation is key to understanding how ice interacts with its bed and how this, in turn, influences the dynamics of ice streams. However, a comprehensive and detailed characterization of this landform's size, shape and spatial arrangement, which might serve to test and refine formational theories, is largely lacking. This paper presents a detailed morphometric analysis and comparison of 4043 MSGs from eight palaeo-ice stream settings: three offshore (Norway and Antarctica), four onshore (Canada), and one from under a modern ice stream in West Antarctica. The length of MSGs is lower than previously suggested (mode 1000–2000 m; median 2892 m), and they initiate and terminate at various locations on an ice stream bed. Their spatial arrangement reveals a pattern that is characterized by an exceptional parallel conformity (80% of all mapped MSGs have an azimuth within 5° from the mean values), and a fairly constant lateral spacing (mode 200–300 m; median 330 m), which we interpret as an indication that MSGs are a spatially self-organized phenomenon. Results show that size, shape and spatial arrangement of MSGs are consistent both within and also generally between different ice stream beds. We suggest this results from a common mechanism of formation, which is largely insensitive to local factors. Although the elongation of MSGs (mode 6–8; median 12.2) is typically higher than features described as drumlins, these values and those of their width (mode 100–200 m; median 268 m) overlap, which suggests the two landforms are part of a morphological continuum and may share a similar origin. We compare their morphometry with explicit predictions made by the groove-ploughing and rilling instability theories of MSG formation. Although the latter was most compatible, neither is fully supported by observations. © 2014 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

KEYWORDS: MSG; glacial bedform; ice stream; morphometry

Introduction

Outlet glaciers and ice streams are fast flowing (up to 1000 m per year) corridors of ice within ice sheets (Bennett, 2003). They are the main arteries through which ice sheets lose mass, accounting for up to 90% of Antarctic discharge, for example (Morgan *et al.*, 1982; Rignot *et al.*, 2011). Ice streams are also dynamic and can widen, migrate or shut down on decadal timescales (Conway *et al.*, 1999; Hulbe and Fahnestock, 2004). Thus, their operation is a key control on ice-sheet mass balance at a range of time-scales. A hierarchy of controls are thought to influence the location of ice streams (Winsborrow *et al.*, 2010), but in most cases, their dynamic behaviour is thought to be influenced by a soft sedimentary bed (Alley *et al.*, 1986; Engelhardt and Kamb, 1997; Tulaczyk *et al.*,

2001). Unfortunately, direct access to the ice-bed interface has only been achieved at a handful of sites along the Siple Coast of West Antarctica (Engelhardt and Kamb, 1997) via costly drilling, which while valuable, provides spatially limited 'point' data. Geophysical techniques provide a valid alternative (Smith and Murray, 2009), but the logistics remain challenging and such techniques have been applied only to a few Antarctic sites, with grids necessarily limited to small (10s km²) areas (King *et al.*, 2009). In contrast, there is an abundance of relatively well preserved palaeo ice stream beds (Winsborrow *et al.*, 2004), which are a useful proxy for the study of ice-bed interactions and which permit easier access to the landforms and sediments created by ice streams. Indeed, there are numerous studies that provide a detailed characterization of palaeo-ice stream beds from

onshore and offshore regions (see reviews in Stokes and Clark, 2001; Livingstone *et al.*, 2012).

Mega-scale glacial lineations (MSGs) are extremely elongated ridges that maintain a parallel conformity over lengths of 10s of km (Clark, 1993). MSGs have been identified for many decades (Lemke, 1958), but were first formally recognized and named by Clark (1993) from Landsat imagery of Canada. Based primarily on their great length, and parallel conformity, they were hypothesized to have formed beneath fast flowing ice streams or surges (Clark, 1993, 1994). Such a proposal gained acceptance after numerous discoveries of MSGs on the Antarctic continental shelf (Shipp *et al.*, 1999; Canals *et al.*, 2000; Wellner *et al.*, 2001) in positions proximal to present-day ice streams. This association has now been verified by radar profiling of the bed of the modern Rutford Ice Stream, West Antarctica (Smith *et al.*, 2007; King *et al.*, 2009) where MSGs were imaged and shown to evolve (e.g. evidence of both erosion and deposition) over a 7 year period. As MSGs have been found in front of and beneath ice streams and evolving during fast ice flow, they are now widely considered to be the key landform signature for identifying palaeo-ice streams (Stokes and Clark, 1999, 2003; Jakobsson *et al.*, 2005; Ottesen *et al.*, 2005b; Stoker and Bradwell, 2005; Przybylski, 2008). The link between MSGs and ice streams has also helped decipher the history of sediment sequences and palaeo geography of continental shelves that are relevant to petroleum and gas exploration (Sejrup *et al.*, 2005; Nygård *et al.*, 2007). Furthermore, MSGs have been identified in ancient (440 million years) sandstones in Africa (Moreau *et al.*, 2005) and, more controversially, on Mars (Lucchitta, 2001; Hubbard *et al.*, 2011).

Despite the importance of MSGs to our understanding of subglacial processes under ice streams, their mechanism of formation is yet to be resolved, although several different ideas have been proposed (Clark, 1993; Tulaczyk *et al.*, 2001; Clark *et al.*, 2003; Schoof and Clarke, 2008; Shaw *et al.*, 2008; Fowler, 2010). Indeed, the formation of MSGs is likely to be important for answering fundamental questions regarding the mechanisms of ice stream flow, such as the role of basal sliding versus subglacial till deformation and how roughness elements evolve and modulate ice stream motion. It has been hypothesized, for example, that enhanced flow within ice streams might be caused by: (i) sliding across the surface of a soft sedimentary bed (Engelhardt and Kamb, 1997); (ii) deforming soft sediments at depths of a few centimetres to several metres (Alley *et al.*, 1986), or (iii) a combination of the two that includes a component of ploughing (Tulaczyk *et al.*, 2001).

Attempts to convert these hypotheses into physically-based numerical models are ongoing (Schoof, 2002; Bougamont *et al.*, 2011), and this is considered a fundamental requirement for constraining predictions of the consequences of global climate change on ice stream dynamics (IPCC, 2007). Thus, the next generation of numerical models should account for the production of MSGs, and be validated through their ability to reproduce MSGs of the correct size and shape. A prerequisite for this, however, is a quantitative characterization of MSGs based on a large and diverse dataset, similar to that which has recently been undertaken for drumlins (Clark *et al.*, 2009; Hess and Briner, 2009; Spagnolo *et al.*, 2010, 2011, 2012). This paper presents the results of detailed morphometric analysis of a sizeable dataset (4043) of MSGs mapped from eight different locations around the world, both onshore and offshore, and both in palaeo and present-day ice stream bed settings. The aim is to provide an inventory of MSG metrics and a robust dataset to both test and develop theories of MSG formation.

A Summary of Previous Work on the 'Metrics' of MSGs

MSGs were initially distinguished and named as a separate type of subglacial landform because of their extraordinary length, well exceeding that of drumlins, flutes and megafutes, but also because of their straight crestline and repetitive parallel arrangement (Clark, 1993). Using Canadian examples, Clark (1993) described them as typically characterized by a length of 8–70 km, width of 200–1300 m and spacing of 300–5000 m. Since then, numerous studies in different parts of the world have expanded the range of MSG metrics: lengths of <1–180 km, widths of 39–5000 m, heights of 1–100 m, elongations (length L/width W) of 2–200:1 and across-flow spacings of 50–5104 m (Table I). However, most previously published work is restricted to qualitative or semi-quantitative descriptions, often only citing minimum and maximum values and, more rarely, estimating mean values, typically expressed as a range or a 'lower than' figure (Table I and references therein). Statistical descriptions of large sample sizes (>100 bedforms) are extremely rare (Graham *et al.*, 2009; Livingstone *et al.*, 2013; Stokes *et al.*, 2013), and very few studies compare data from different ice stream beds (Ottesen *et al.*, 2005b).

Methods

The MSG database was assembled from a total of eight study areas (Table II; Figure 1) that have been previously identified as ice stream beds with abundant MSGs (Winsborrow *et al.*, 2004, 2012; Graham *et al.*, 2009; King *et al.*, 2009; Brown *et al.*, 2011; Jakobsson *et al.*, 2011, 2012). Although MSGs have previously been reported from these regions, they have never been systematically mapped or analyzed in detail.

Datasets

Offshore, three palaeo ice stream beds were studied: two located beneath the Amundsen Sea, Antarctica (Pine Island, and Getz), and one under the Barents Sea, off northern Norway (Håkerringdupet). These marine datasets were chosen because of the availability of high resolution 3D terrain data (Table II, Figure 1(A), (B), (C), (E)).

Pine Island trough comprises two distinct sets of MSGs belonging to distinct ice streaming events and which are separated by a grounding zone wedge (Jakobsson *et al.*, 2012). In this paper, the northernmost set has been called 'Pine Island N', and the southernmost 'Pine Island S'. Together, they cover about 40% of the entire Pine Island trough length, and are located in its middle to outer portion. The area is covered by terrain data with horizontal resolution of 20 m and vertical resolution of ~2 m, collected using a hull-mounted Kongsberg 12 kHz EM122 multibeam echo-sounder. The Getz area comprises one set of MSGs from the inner to middle shelf part of the ice stream pathway. The middle-to-outer shelf is either iceberg scoured or unsurveyed. The ice stream trough (from present-day ice-shelf front to the continental shelf break) is ~280 km long, and the MSGs used in this study cover a ~65 km long portion of it (providing data across most of the ice stream width). The area has terrain data which was collected in 2006 by hull-mounted Kongsberg EM120 and Atlas Hydrosweep DS-2 multibeam swath systems. The combined data are gridded at 30 m bin size, well within the capability of both systems at these shelf water depths (~700 m). Depth resolution for the echo-sounders is 0.1 m for both systems and vertical resolution of the gridded output is ~2 m. MAREANO

Table 1. Metrics of MSGs as reported in previous papers (in order of publication year). Note that most refer to minimum and maximum values and when mean values are indicated, these are often estimates ('es' on the table next to the values)

ID	paper	position	area	length (km)			width (m)			amplitude (m)			elongation ratio			spacing (m)		
				min	mean	max	min	mean	max	min	mean	max	min	mean	max	min	mean	max
1	Lemke, 1958	onshore	North Dakota, USA	-	-	20	-	-	-	2	-	25	-	60:1 (es)	-	-	-	-
2	Clark, 1993	onshore	various, Arctic Canada	8	-	70	200	-	1300	-	-	-	-	-	-	300	-	5000
3	Shipp <i>et al.</i> , 1999	offshore	Ross Sea, Antarctica	20	-	-	-	-	-	-	-	-	-	-	-	300	-	650
4	Rise <i>et al.</i> , 1999	offshore	Skagerrak, Norwegian shelf	20	-	-	-	-	-	10 (es)	-	-	-	-	-	100	-	300
5	Canals <i>et al.</i> , 2000	offshore	Antarctic Peninsula	-	-	100	1000	-	3000	-	40 (es) max?	-	-	-	-	-	-	-
6	Pol yak <i>et al.</i> , 2001	offshore	Central Arctic Ocean	-	-	15	-	-	-	-	-	-	-	-	-	50	-	200
7	Wellner <i>et al.</i> , 2001	offshore	Antarctica, various	-	10s (es)	-	-	400 (es)	-	15	-	20	-	-	-	-	-	-
8	Ó Cofaigh <i>et al.</i> , 2002	offshore	Antarctic Peninsula	10	-	170	130	-	400	-	-	-	30:1	-	90:1	-	-	-
9	Stokes and Clark, 2003	onshore	Dubawnt Lake, Arctic Canada	-	1.8	12.7	-	256	990	-	-	-	7:1	48:1	-	-	-	-
10	Clark <i>et al.</i> , 2003	offshore	Antarctic Peninsula	-	30 (es)	100	-	-	-	2	14	60	-	-	-	451	625	705
11	Evans <i>et al.</i> , 2004	offshore	Antarctic Peninsula	3	-	4.2	-	-	450	-	-	-	11:1	-	21:1	-	-	-
12	Dowdeswell <i>et al.</i> , 2004	offshore	Antarctic Peninsula	10	-	17	130	-	400	2	-	6	-	-	-	-	-	-
13	Andreassen <i>et al.</i> , 2004	offshore	Barents Sea	-	-	38	50	-	360	-	-	10	-	-	105:1	-	-	-
14	de Angelis and Kleman, 2005	offshore	M'Clintock Channel, Nunavut, Arctic Canada	8	-	11	500	-	2000	-	-	-	-	-	-	-	-	-
15	Ottesen <i>et al.</i> , 2005a	offshore	Vestfjorden-Traenadjupet, Norwegian shelf	-	-	-	200	-	500	5	-	10	-	-	-	300	-	700
16	Ottesen <i>et al.</i> , 2005b	offshore	Skagerrak, North Sea	10	-	-	-	150-400 (es)	-	-	2-5 (es)	12	-	-	-	-	200-600 (es)	-
			NE North Sea Plateau	-	-	-	-	-	-	<5 (es)	10	-	-	-	-	100-500 (es)	-	
			Froybankhola, Norwegian shelf	5	-	-	-	150	-	<5 (es)	8	-	-	-	-	300	-	
			Haltenbanken S, Norwegian shelf	-	-	9	-	120	-	<3 (es)	5-10 (es)	-	-	-	-	220	-	
			Sula Ridge, Norwegian shelf	-	-	5	-	150	-	< 10 (es)	15	-	-	-	-	300	-	
			NE of Skjoldryggen, Norwegian shelf	15	-	-	-	170	-	<5 (es)	10	-	-	-	-	260	-	
			Traenadjupet, Norwegian shelf	10	-	-	-	250	-	<5 (es)	10	-	-	-	-	400-500 (es)	-	
			Vestfjorden, , Norwegian shelf	10	-	-	-	200-500 (es)	-	5-10 (es)	-	-	-	-	-	500-700 (es)	-	
			Andfjorden, Norwegian shelf	-	-	13	-	210	-	< 3 (es)	5	-	-	-	-	370	-	
			Barents Sea	-	-	35	-	3000	-	-	-	10	-	-	-	3700	-	
			Isfjorden, Svalbard	5	-	-	-	350	-	<5 (es)	8	-	-	-	-	500-700 (es)	-	
			Kongsfjorden, Svalbard	4	-	-	-	410-470 (es)	-	2-5 (es)	10	-	-	-	-	450-800 (es)	-	
			Wijdefjorden, Svalbard	-	-	5	-	260	-	2-4 (es)	10	-	-	-	-	480	-	
17	Jakobsson <i>et al.</i> , 2005	offshore	area B, Chukchi Borderland, Arctic	-	-	-	214	407	913	-	-	-	-	-	-	-	-	
			area C, Chukchi Borderland, Arctic	-	-	-	240	-	1000	-	-	-	-	-	-	-	-	
18	Evans <i>et al.</i> , 2005	offshore	Larsen-A shelf, Antarctic Peninsula	1.6	-	9.2	90	-	220	-	-	-	-	-	-	-	-	
			Larsen Inlet, Antarctic Peninsula	2.1	-	8.6	130	-	390	-	-	-	-	-	-	-	-	
			P. Gustav Channel, Antarctic Peninsula	2.6	-	23	160	-	520	-	-	-	-	-	-	-	-	
			In. Robertson Trough, Antarctic Peninsula	6.2	-	9.9	100	-	400	-	-	-	16:1	-	40:1	-	-	
			Out. Robertson Trough, Antarctic Peninsula	5.7	-	11.2	140	-	400	-	-	-	-	-	-	-	-	

(Continues)

Table 1. (Continued)

ID	paper	position	area	length (km)			width (m)			amplitude (m)			elongation ratio			spacing (m)		
				min	mean	max	min	mean	max	min	mean	max	min	mean	max	min	mean	max
19	Ó Cofaigh <i>et al.</i> , 2005	offshore	Antarctic Peninsula	10	-	22	-	-	-	2	3	8	-	-	-	150	305	550
20	Heroy and Anderson, 2005	offshore	Antarctic Peninsula	-	-	22	-	-	-	10	-	20	-	-	80:1	200	300	600
21	Wellner <i>et al.</i> , 2006	offshore	Antarctic Peninsula various Antarctica	-	-	-	-	-	-	2	-	20	-	-	-	100	-	900
22	Evans <i>et al.</i> , 2006	offshore	Pine Island Bay, Antarctica	6.8	-	10	160	-	420	-	-	-	18:1	-	60:1	-	-	-
23	Domack <i>et al.</i> , 2006	offshore	Antarctic Peninsula	30	-	120	-	-	-	25 (es)	-	-	-	-	-	2000 (es)	-	-
24	McMullen <i>et al.</i> , 2006	offshore	Mertz Trough, E Antarctica	14	-	20	-	500 (es)	-	-	20 (es)	-	-	-	-	1000	-	1500
25	Andreassen <i>et al.</i> , 2007	offshore	Barents Sea 180 500 5000 4 9 85:1	-	-	180	500	-	5000	4	-	9	-	-	85:1	-	-	-
26	Graham <i>et al.</i> , 2007	offshore	Witch Ground Basin, North Sea	5	-	20	50	-	120	-	10-12 (es)	-	-	50:1 (es)	150:1	100	-	-
27	Ottesen <i>et al.</i> , 2007	offshore	Svalbard	< 1	-	10	-	-	-	-	-	15	-	-	-	100	-	2000
28	Andreassen <i>et al.</i> , 2008	offshore	Bjørnøyrenna, SW Barents Sea, Ingøydjupet, SW Barents Sea, Djuprenna, SW Barents Sea	-	-	180	2000	-	5000	-	-	10	-	-	40:1	-	-	-
				-	-	120	500	-	3500	4	-	5	-	-	33:1	-	-	-
				-	-	180	-	-	800	-	-	9	-	-	85:1	-	-	-
29	Ottesen <i>et al.</i> , 2008	offshore	Svalbard	-	-	1	-	-	200	-	-	5	-	-	-	-	-	-
30	Ottesen <i>et al.</i> , 2008b	offshore	N Norwegian shelf	3	-	40	200	-	1200	1	-	30	10:1	-	-	250	-	3000
31	Engels <i>et al.</i> , 2008	offshore	Arctic Ocean	-	-	10	-	50 (es)	-	-	-	-	-	-	200:1	-	-	-
32	Andreassen and Winsborrow, 2009	offshore	Barents Sea	-	-	38	50	-	360	-	-	10	-	-	100:1	-	-	-
33	Graham <i>et al.</i> , 2009	offshore	Getz B, Amundsen Sea, Antarctica	1	-	20	100	-	500	-	-	50	-	-	45:1	-	-	-
			Getz A, Amundsen Sea, Antarctica	1	-	15	100	-	400	10	-	100	5:1	-	70:1	-	-	-
			Mid/outer shelf, Amundsen Sea, Antarctica	6	-	38	131	-	451	2	5-10 (es)	18	25:1	-	140:1	80	-	>300
34	Ross <i>et al.</i> , 2011	both	Coats Island, Hudson Bay, Canada	-	-	20	-	600-800 (es)	-	-	-	-	-	28:1 (es)	-	-	-	-
35	Rebesco <i>et al.</i> , 2011	offshore	Kveithola trough, Barents Sea	-	-	8	100	-	600	-	-	15	-	-	10:1	-	-	-
36	Ruther <i>et al.</i> , 2011	offshore	Bjørnøyrenna, Barents Sea	20	-	40	1500	-	4000	5	-	10	-	-	-	5000 (es)	-	-
37	Larter <i>et al.</i> , 2012	offshore	Weddell Sea, Antarctica	-	-	18	-	-	-	2	-	12	-	-	60:1	250	-	2500
38	Winsborrow <i>et al.</i> , 2012	offshore	SW Barents Sea	0.3	2.2	20	500	-	1000	-	-	-	-	-	-	-	-	-
39	Greenwood <i>et al.</i> , 2012	offshore	Ross Sea, Antarctica	0.3	1	3.2	-	-	-	2	-	5	-	-	-	-	-	-
40	Stolldorf <i>et al.</i> , 2012	offshore	Ronne Trough, Weddell Sea, Antarctica	12	-	-	-	-	-	4	-	10	100:1	-	-	200	-	500
			Hughes Trough, Weddell Sea, Antarctica	22	-	-	-	-	-	4	-	7	50:1	-	-	300	-	600
41	Stokes <i>et al.</i> , 2013	onshore	Dubawnt Lake, Arctic Canada	0.2	0.9	20.1	39	117	553	-	-	-	2:1	9:1	149:1	-	-	-

(www.mareano.no) multibeam data, collected by the Norwegian Hydrographic Service (horizontal resolution of 5 m, vertical resolution of ~5 m), were used in the Håkjerringdjupet area. The area comprises one main set of MSGs (Winsborrow *et al.*, 2012) covering about 30% of the entire palaeo ice stream.

Four previously recognized palaeo-ice stream beds were studied from onshore settings (Winsborrow *et al.*, 2004; Brown *et al.*, 2011) and selected for mapping due to the excellent preservation of MSGs in these regions and the lack of cross-cutting landform relationships (Table II; Figure 1(F), (G), (H), (I)). All

four are situated in north-west Canada, where ice streaming is thought to have contributed to the low ice surface profile and rapid retreat of the Laurentide Ice Sheet (Beget, 1987; Brown *et al.*, 2011). The areas are covered by Landsat ETM+ and SPOT satellite images with a horizontal resolution of 15 and 10 m, respectively. Unlike their onshore counterparts, these palaeo ice streams are not situated in topographic troughs, thus making it difficult to quantify what percentage of the original ice stream bed is covered by the analyzed MSGs.

MSGs from the bed of the Rutford Ice Stream in West Antarctica were also mapped (King *et al.*, 2009), which is the only extant ice stream for which high resolution bed data are available (Table II; Figure 1(D)). Radar data were acquired perpendicular to flow and have an along-track spatial resolution of 7.5 m, and a vertical resolution of 3 m. Profiles were spaced at 500 m intervals in the along-flow direction and an interpolated surface was created using a 20-m-perpendicular-to-flow x 200-m-parallel-to-flow grid. This interpolation scheme maintains the continuity of features elongated in the flow direction, while preserving the high spatial sampling of the cross-flow bed profile. The surface representing the bed was then re-sampled at 50 x 50 m spacing to form the digital terrain model used in this analysis. The data covers the lowermost portion of the Rutford Ice Stream, 25% of its total area.

Mapping techniques

MSGs were mapped from high-resolution bathymetric data (offshore), radar data (extant ice stream), and combined satellite images (onshore). Bathymetric and radar data were converted into digital terrain models and visualized as hill-shaded images with different illumination angles and elevations, as well as various vertical exaggerations, following a standardized method for mapping glacial bedforms (Smith and Clark, 2005). Due to a lack of similar high resolution digital terrain models onshore, MSGs could only be mapped from satellite images. Improved identification of subtle landforms was achieved by using two different satellite sources and by (locally) stretching the contrast of these images. All landforms were mapped at a scale between 1:30 000 and 1:40 000, depending on the resolution of the terrain or satellite data.

Offshore and modern (Rutford) MSGs are characterized by a continuous series of parallel crests separated by troughs or grooves. No evident breaks of slope are present to help delineate individual landform side-boundaries and MSGs appear as a continuous rolling or waved surface, i.e. a sinusoidal profile in cross-section. Therefore, they were mapped as lines drawn along their crests (Figure 2(A)–(B)).

In all onshore settings, satellite images made it possible to identify MSGs as individual features with distinct boundaries (Figure 2(C)–(D)) highlighted by shadows and by a change in colour which corresponds to a change in vegetation and soil moisture (corresponding to a break in slope). Onshore MSGs were therefore mapped as both lines along their crests (to compare with the offshore data) and as elongate polygons.

Measuring MSGs

The azimuth of all mapped MSGs ($n = 4043$) was automatically derived with specific GIS tools as the angle (0 – 360°) from grid North of each digitized line. Crestline length was evaluated from the total length of each MSG crest line. Not all of the mapped MSGs could be mapped for their entire extent (see also following section). These MSGs were not included in the

length analysis, which was therefore limited to a total of 3068 features. Width and elongation could only be extracted from the polygon data from onshore settings ($n = 1929$). Width was estimated using Euler's approximation for the width of an ellipse (Clark *et al.*, 2009). Elongation was computed as length/width.

The across-flow spacing of MSGs is the distance between adjacent crestlines. MSGs are relatively long features, and some variation in lateral spacing along their extent has been noted. Therefore, multiple values (on each side) were regularly collected at 1 km intervals along each MSG, by creating a series of 1 km spaced topographic profiles transverse to crestlines (Figure 3). The cross-profile interval represents a compromise between attempting to take multiple measurements along each individual MSG and maintaining the time needed to process all data efficiently. With the 1 km cross-profile spacing, mean lateral spacing of MSGs was obtained by typically averaging eight (four on each side) spacing values measured along individual MSG. A semi-automated GIS procedure was then applied to determine the distance between adjacent crestlines along each profile (Figure 3). Two spacing measurements (i.e. the distance to each lateral neighbour) were collected at each interception point between a cross-profile and a MSG crestline. Data were therefore summarized by calculating a mean MSG spacing from these measurements. Only those MSGs that had two adjacent neighbours (and that were not separated from these by large erosional features like meltwater channels or a field of iceberg furrows) were included in this analysis (1697 offshore and 1846 onshore). In addition, in order to assess how across-flow spacing varies downstream, a mean spacing was also determined for individual cross-flow profiles in the down-flow direction.

MSG amplitude was defined as the difference between the elevation of the crestline and the lowest elevation recorded in the trough between adjacent MSG crestlines on both sides of each MSG (Figure 3). The same 1 km spaced cross-profiles used to measure spacing were employed for this task. The two amplitude values generated at each cross-profile interception point were averaged in order to produce a single value, an effective way to de-trend the variation in elevation due to the regional-scale topography. All intersection values were then averaged for each MSG. Note, however, that amplitude could only be measured for the offshore MSGs (for which a high resolution terrain model was available) and the same criteria were applied to dictate where spacing was measured ($n = 1697$). In order to assess how amplitude varies downstream, the mean amplitude was also determined for individual cross-flow profiles in the down-flow direction.

Data fidelity

MSGs have likely experienced post-glacial modification. Attempts to quantify post-glacial erosion, current winnowing, glacialine sediment draping, etc., are challenging and extremely rare (Kirshner *et al.*, 2012; Finlayson, 2013). However, other modifications are easier to recognize (e.g. iceberg furrows, meltwater channels, etc.) and their influence on the derived metrics could be considerable. Where possible, these have been taken into account. For example, only fully imaged MSGs (i.e. exclude those running off the edge of image domains) and those without a clear sign of being partly overridden (e.g. by moraine) or eroded (e.g. subsequent meltwater channel) were included in the length analysis. Similarly, spacing and amplitude were determined only for MSGs showing continuity (i.e. no interruptions due to the presence of iceberg furrows or meltwater channels) between adjacent features.

The frequency distributions of MSG metrics from different settings were assembled into single histograms (Figure 4). In

Table II. Details of the location of the 9 analyzed ice stream beds, including the number of mapped MSGSLs and the characteristics of the source images/digital terrain models (bsl = below sea level; bgl = below ground – ice surface – level; asl = above sea level)

ID	REGION	SUB-REGION	ICE STREAM	POSITION	LATITUDE	LONGITUDE	ELEVATION RANGE	AREA ANALYSED	MAPPED AS	CONTEXT	DATA TYPE	HORIZONTAL GRIDGING	VERTICAL RESOLUTION
A, B	Antarctica	Amundsen Sea	Pine Island	offshore	72.9°	S 107.1°	W 672–922 m bsl	~ 1150 km ²	lines	palaeo	bathymetric multibeam	20 m	~ 2 m
C	Antarctica	Amundsen Sea	Getz shelf	offshore	73.3° S	115.3° W	717–1016 m bsl	~ 900 km ²	lines	palaeo	bathymetric multibeam	30 m	~ 2 m
D	Antarctica	West Antarctica	Rutford	subglacial	79°	S 81° W	1220–2474 m bgl	~ 750 km ²	lines	active	mono-pulse ground radar	7.5 m	~ 3 m
E	Norway	Barents Sea	Håkerringjdupet	offshore	70.5° N	18.3° E	224–278 m bsl	~ 350 km ²	lines	palaeo	bathymetric multibeam	5 m	~ 5 m
F	Arctic Canada	NW Territories	Great Bear	onshore	64.8° N	123.0° W	180–470 m asl	~ 7200 km ²	lines & shapes	palaeo	Landsat and Spot images	15 and 10 m	-
G	Arctic Canada	NW T./Alberta	Cameron	onshore	60.1° N	117.6° W	610–740 m asl	~ 600 km ²	lines & shapes	palaeo	Landsat and Spot images	15 and 10 m	-
H	Arctic Canada	NW Territories	Liard	onshore	61.2°	N 121.4°	W 270–380 m asl	~ 350 km ²	lines & shapes	palaeo	Landsat and Spot images	15 and 10 m	-
I	Arctic Canada	NW Territories	Haldane	onshore	67.8° N	121.5° W	190–270 m asl	~ 750 km ²	lines & shapes	palaeo	Landsat and Spot images	15 and 10 m	-

order to avoid bias associated with settings with a greater number of measurements, the data were normalized according to the relative number of MSGSLs of each setting.

Results

The metrics of the MSGSL are presented in Table III for each study area and as an aggregated population for all mapped MSGSLs. Statistics from each setting and normalized frequency histograms are shown in Figure 4.

MSGSLs are characterized by lengths of up to 37 km and elongation ratios of up to 134:1 (Table I). However, although these maximum values have been commonly reported in previous work, they are not representative of the vast majority of sampled features. Moreover, these extreme values can strongly affect mean values, which also become unreliable statistical descriptors when frequency distributions are skewed, as is the case here. Consequently, a simpler and better way to describe their metrics is to focus on modal and median values and to provide a most common range, i.e. 10 and 90 percentiles.

Parallel conformity

The vast majority (80%) of all studied MSGSLs have an azimuth within μ (mean value) $\pm 5^\circ$, confirming the high level of parallel conformity described by many but rarely quantified (Clark, 1993). The narrowest azimuth distributions are found in Pine Island trough and on the Liard palaeo ice stream beds (all three with 80% of the population within just 5°). The broadest azimuth distributions (with a range of 18° and 19° , respectively) are found in the Getz and Håkerringjdupet palaeo ice streams, where MSGSLs are not straight but can be observed to bend, following a curving ice flow trajectory. However, even in these settings, the parallel conformity within adjacent MSGSLs remains striking (Figure 1(D)).

Length, width and elongation

For 80% of MSGSLs, length is between 940 and 9050 m (with a mode of 1000–2000 m and median of 2890 m). Frequency distributions of length for individual study areas are typically unimodal with a positive skew (i.e. a long, ~exponentially decreasing tail after the mode) and this can also be seen in the total population. Individual ice stream beds reveal median values ranging from 750 m (Håkerringjdupet) to 4480 m (Great Bear).

The vast majority (80%) of MSGSLs have widths of 90–720 m (mode 100–200 m and median 270 m). The frequency distribution of all MSGSLs is unimodal and positively skewed. Median widths for MSGSLs varies from 90 (Cameron Hills) to 510 m (Great Bear).

Most (80%) MSGSLs have elongations between 6 and 33:1 (with a mode of 6–8:1 and median of 12:1). The frequency distribution of elongation is unimodal and positively skewed. For individual ice stream beds, median elongations vary from 10:1 (Great Bear and Haldane) to 25:1 (Liard).

Spacing

For 80% of MSGSLs, their spacing is between 140 and 960 m (mode of 200–300 m and median of 330 m). When all data are plotted in a single frequency histogram (bin width of 100 m), the distribution is unimodal with a positive skew. Most individual ice stream beds are characterized by MSGSLs spaced apart between 200 m and 400 m, with the exception of the

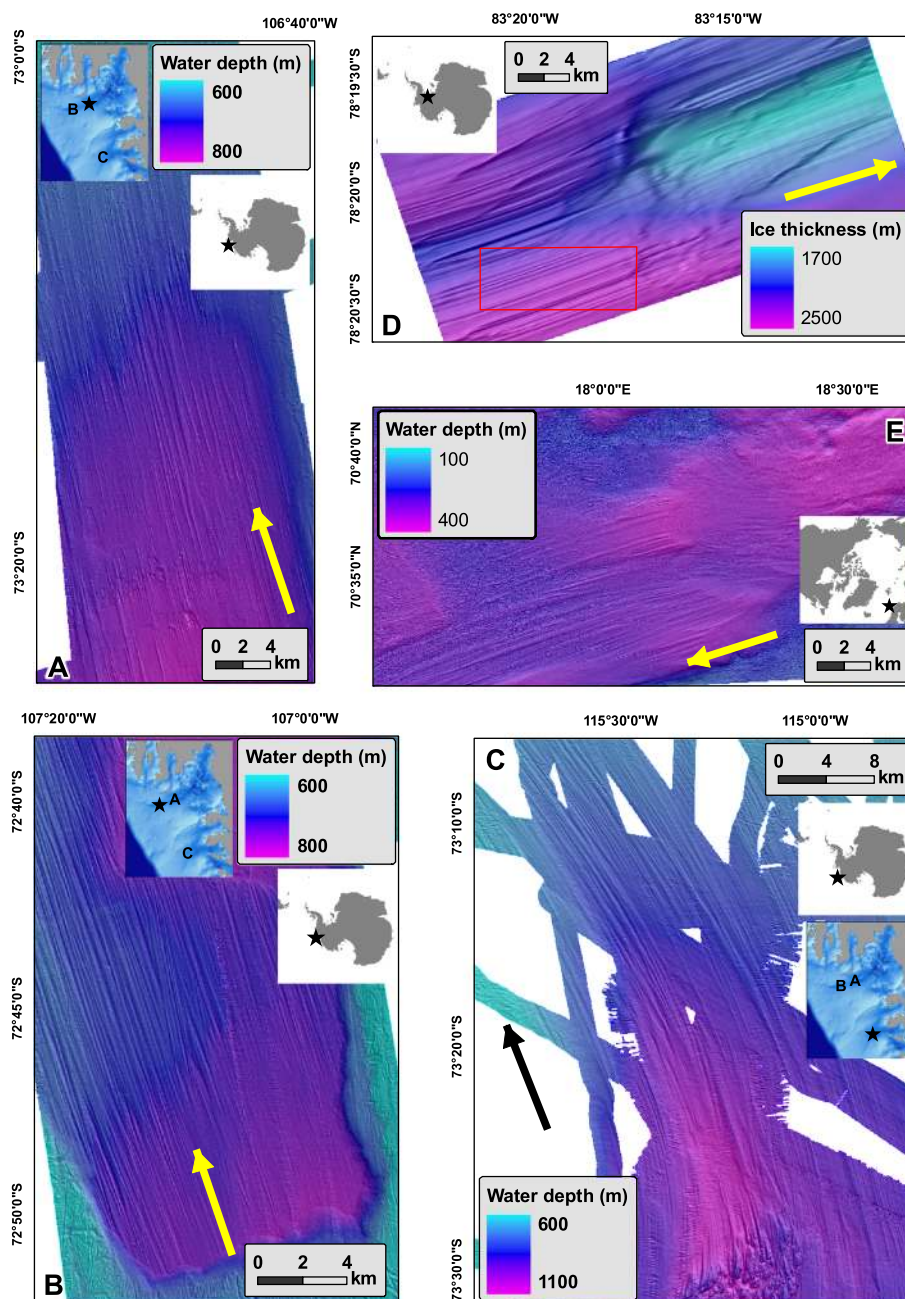


Figure 1. Overview of the ice stream beds analysed in this paper. A (letter codes refer to Table II): Pine Island S; B: Pine Island N; C: Getz; D: Rutford (the red box represents the area shown in Figure 3); E: Håkerringjdupet; I: Haldane; H: Liard; F: Great Bear; G: Cameron Hills. A, B, C and E are marine datasets, D is under existing ice stream and I-G are terrestrial datasets. Terrain images hillshaded from various bathymetric and radar data (A-E). Satellite images from Landsat ETM+ false colour (4,3,2) composites with superimposed SPOT panchromatic band (I-G). Arrows show the direction of ice flow. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Great Bear palaeo ice stream bed where the median value is 840 m. Over short distances (1 km), the spacing of most ice stream settings shows high variability in the downstream direction. However, over long distances (whole settings) four out of nine study areas show a statistically significant spacing trend (with a 99% confidence interval) (Table IV; Figure 5) in the downstream direction. Of these, the Great Bear, Pine Island N and Getz MSGSLs show decreasing mean spacing, while Haldane shows increased mean spacing moving downstream.

Amplitude

The vast majority (80%) of MSGSLs have amplitudes between 1 m and 9 m (with a mode of 1–2 m and median of 3 m). The

frequency distribution for all MSGSLs is unimodal with a positive skew. While the Rutford Ice Stream bed shows a high median value of 8 m, all other ice streams are characterized by a median amplitude between 2 and 3 m. The downstream variation of mean amplitude is usually of the order of a few metres (Figure 5), with the exception of the sudden 10 m increase about 23 km downstream along the Rutford Ice Stream bed (Figure 5), likely related to the presence of a bedrock bump (King *et al.*, 2009). Different ice streams reveal different trends (Table IV; Figure 5). The most statistically-significant trend is that of the Pine Island N ice stream bed, where MSGSL amplitude shows a tendency to increase downstream. Other significant trends (within the 99% confidence interval) are those revealed by the Håkerringjdupet and Getz ice stream beds, the former showing increasing amplitude (and variability), while the latter shows decreasing amplitude downstream. It should also

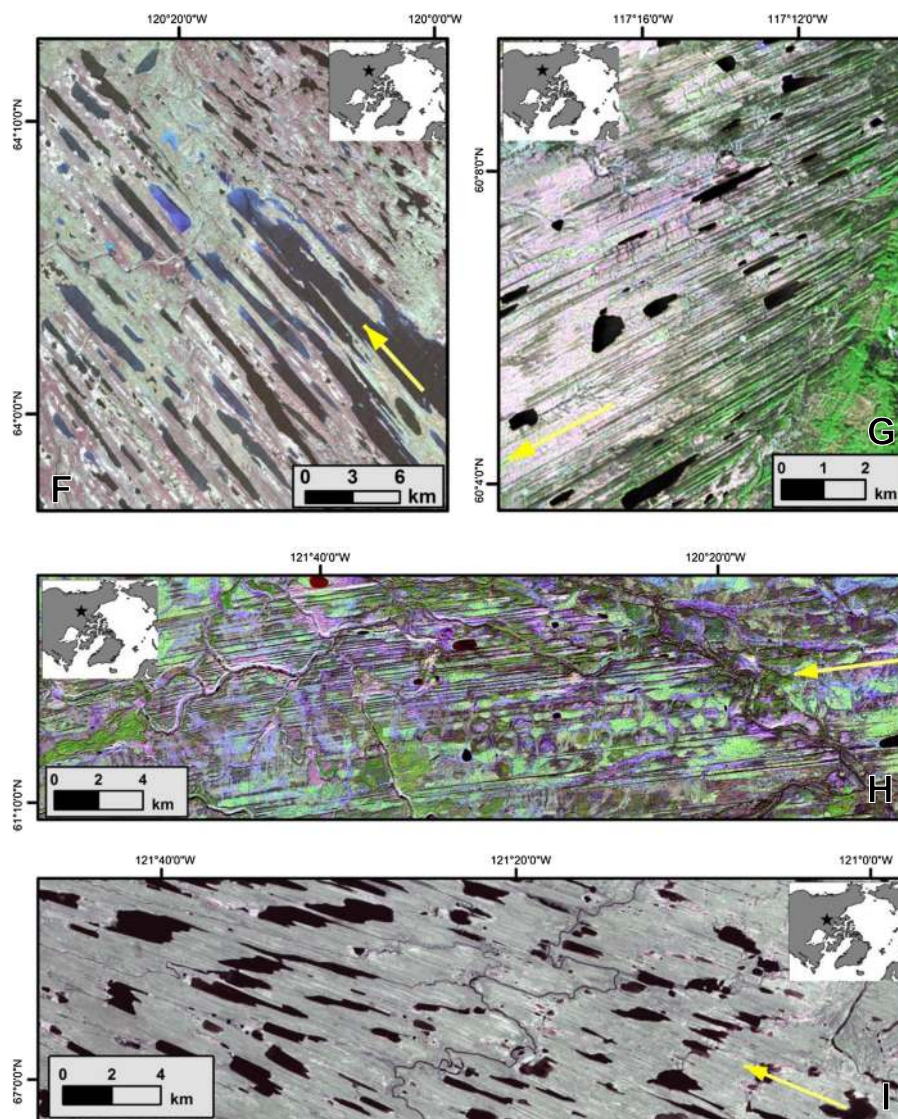


Figure 1. Continued

be noted that a trend of decreasing amplitudes exists before and after the bedrock bump (at 23 km) on the Rutford Ice Stream bed (Figure 5).

Discussion

Metrics

Taken together, the metrics presented here quantitatively confirm MSGs as kilometre-long, highly elongate features with amplitudes of only a few metres (mode of 1–2 m) and a close and consistent spacing with a high parallel conformity. Their low amplitude and great length explains why MSGs are typically not visible in the field and can only be fully appreciated and mapped from airborne and spaceborne imagery (Clark, 1993), or shipborne bathymetry.

Consistency

All measured variables show a unimodal distribution within each setting, thus indicating a prominent scaling preference rather than an even spread of values across a wide scale range or a multimodal distribution. Comparing distributions between ice stream settings reveals a strong consistency in the production of MSGs of similar size, shape and spacing. With a few exceptions where local factors might have had an influence on specific metrics

(e.g. Great Bear MSGL width), MSGL metrics were found to be very similar and always within the same order of magnitude. In some cases (e.g. spacing, Figure 5) the statistics are so strikingly close that there is virtually no difference between MSGs from offshore Antarctica and onshore Arctic Canada. This is particularly remarkable because some of the settings are thousands of kilometres apart, and each was subjected to a specific glacial history (duration of flow, evolving ice thickness and velocity) and specific local topographic, sedimentary and lithological conditions. We interpret this consistency within and across the settings to indicate that MSGs share a common origin, which is largely insensitive to local factors.

MSGL length

MSGs are known for being extremely long features. The present study confirms this idea (maximum length 37 km), but also scales down the proportions by indicating that the vast majority (80%) of MSGs are less than 9 km long (see Stokes *et al.*, 2013). This figure is almost one order of magnitude lower than reported in previous studies (Table I), although these often describe MSGs by the maximum length measured within a field of MSGs. This difference is also largely due to the fact that MSGs have been mapped here in unprecedented detail, making it possible to identify and separate smaller features. Indeed, what generally appears to be a single feature at a small scale (e.g. 1:70 000), often reveals

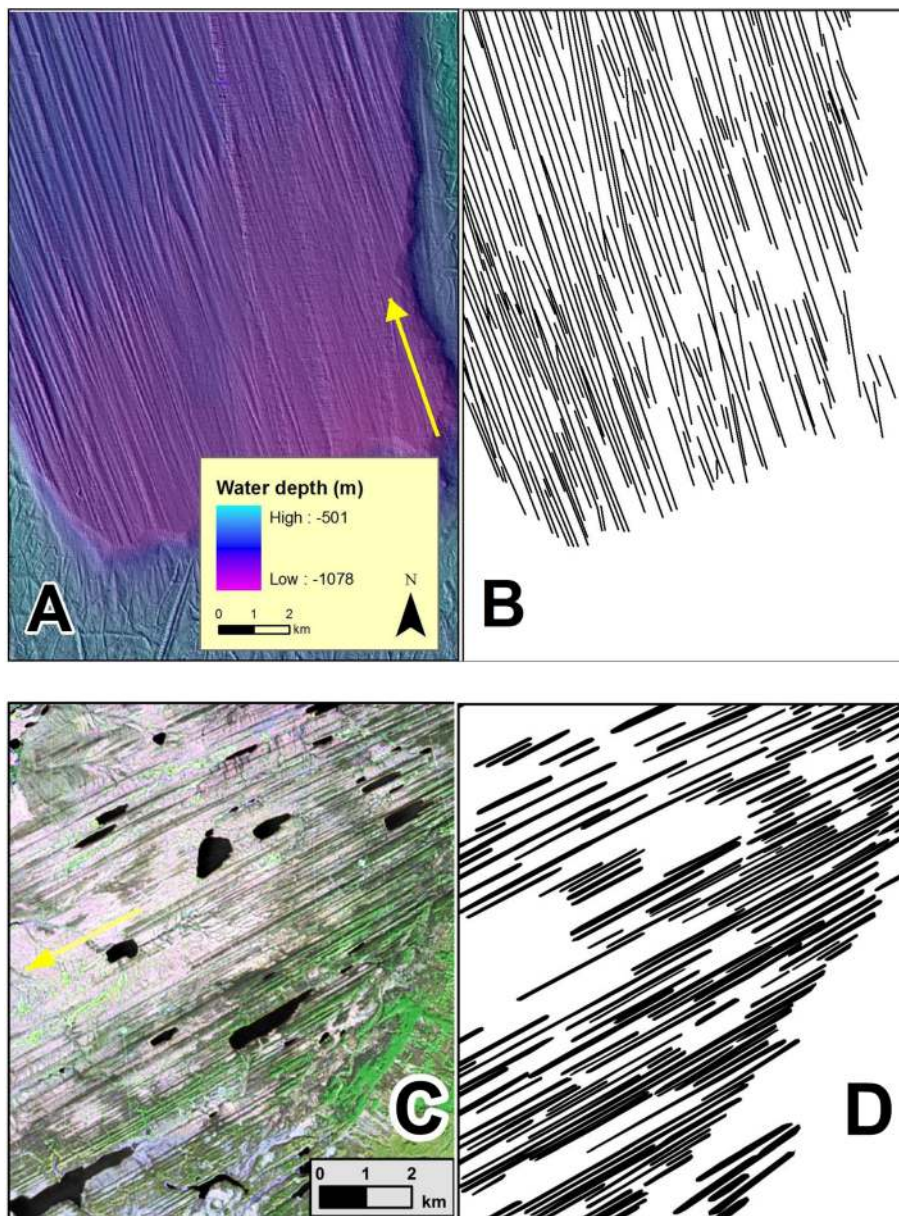


Figure 2. Examples illustrating the different mapping of MSGs in different study areas that was dictated by the availability of imagery. Lines along the crests offshore (Pine Island Bay, A and B on the figure) and polygons onshore (Great Bear Ice Stream, C and D on the figure). Arrows indicate the inferred palaeo direction of ice flow. This figure is available in colour online at wileyonlinelibrary.com/journal/esp

itself to be the sum of two or more aligned, but clearly-separated (by some tens of metres), landforms at a larger scale (e.g. 1:30 000).

A fundamental consequence of lineations sets extending up to hundreds of kilometres (Mosola and Anderson, 2006) and individual MSGs being shorter than hitherto supposed is that multiple features exist at different downstream positions throughout the extent of an ice stream. In other words, individual MSGs are not found to extend continuously throughout an ice stream bed, i.e. from its upstream to the downstream ends. Rather, they terminate and others initiate in multiple locations (Figure 7).

Comparison with drumlins

The length and the elongation of MSGs are typically higher than drumlins (Clark *et al.*, 2009), whereas the amplitude is about half as much as a typical drumlin relief (Spagnolo *et al.*, 2012). However, other metrics, such as the width (compared with Clark *et al.*, 2009) and the spacing are very similar to drumlins. In particular, the similarity in width but larger lengths are supportive of the argument that MSGs could represent extremely elongate drumlins (Stokes and Clark, 2002) and that

a similar mechanism might produce both MSGs and drumlins, depending on the ice flow velocity (Clark, 1993; Stokes *et al.*, 2013) and the nature and availability of sediment (Ó Cofaigh *et al.*, 2005). Indeed, there are now many documented palaeo ice stream settings, both onshore (Stokes and Clark, 2002; Stokes *et al.*, 2013) and offshore (Ó Cofaigh *et al.*, 2002; Heroy and Anderson, 2005; Graham *et al.*, 2009), where drumlins upstream become progressively more elongate and into MSGs downstream, thus making a distinction between the two landforms very difficult.

Log-normal distributions

Like drumlins (Clark *et al.*, 2009), the metrics of MSGs show a unimodal frequency distribution with a positive skew. When length, amplitude or spacing for a population of MSGs are converted into their natural logarithm and their frequency evaluated for bins of equal intervals (Figure 6), the resulting frequency distribution is log-normal, in common with drumlins (Fowler *et al.*, 2013; Hillier *et al.*, 2013). This type of distribution is frequent in nature, with examples from many disciplines, including geology and mining (e.g. concentration of elements), biology (e.g.

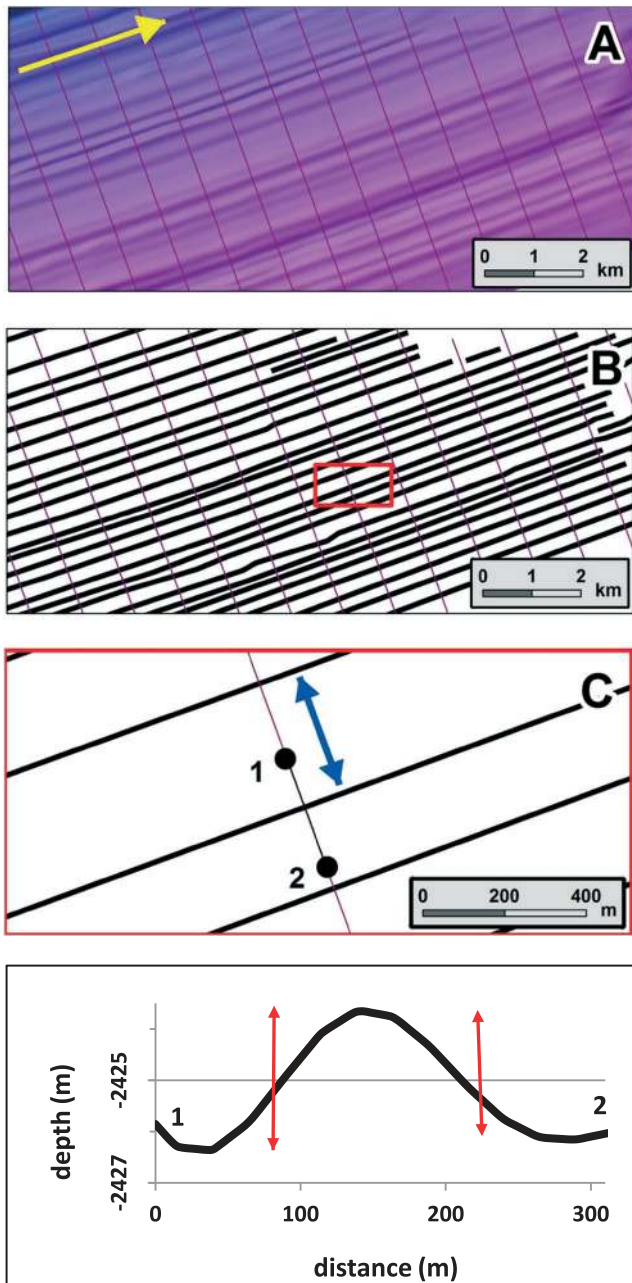


Figure 3. Spacing and amplitude determination using Rutford ice stream bed (see red box in Figure 1 for map overview). (A) hillshaded bathymetric data; the purple lines represent cross-sections spaced 1 km apart, while the yellow arrow indicates the direction of ice flow; colours refer to bathymetric scale of Fig. 2(A). (B) MSGLs mapped along their crestlines (black lines); red rectangle represents the area in C. (C) Blue arrow indicates MSGL spacing. Point 1 and 2 refer to the cross-section shown in D. (D) MSGL cross-section 1–2; red arrows indicate the amplitude measured as the difference in elevation between the crestline and adjacent low points in troughs (two values per MSGL). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

airborne contamination by bacteria and fungi), human medicine (e.g. latency period of diseases) and ecology (e.g. species abundance) (Limpert *et al.*, 2001 and references therein). Typically, log-normal distributions emerge from variables that are characterized by an incremental ('multiplicative') growth or fragmentation, but that initiated as a large number of independent events (Limpert *et al.*, 2001). The log-normal distribution implies an element of randomness in the growth/decay of MSGLs, similar to that which has been advocated for ribbed moraines (Dunlop *et al.*, 2008) and argued for drumlins (Fowler *et al.*, 2013; Hillier *et al.*,

2013). In view of this, MSGLs are likely to represent a growing phenomenon for which the growth phases occur randomly, or for random durations, or under variably random physical conditions of the flow parameters (Hillier *et al.*, 2013).

Wider implications

MSGL formation theories

The formation of MSGLs is enigmatic, despite their importance for understanding ice stream dynamics. Different formational hypotheses/ideas have been proposed, some invoking an erosional mechanism (Lemke, 1958) while others suggesting a constructional process (Bluemle *et al.*, 1993), perhaps involving the deformation of subglacial sediment (Clark, 1993). Some advocate a prominent role for ice ploughing through sediment (Tulaczyk *et al.*, 2001; Clark *et al.*, 2003), while others consider water, either in terms of a mega-flood (Shaw *et al.*, 2008) or a smaller film between ice and sediment that breaks down into a series of rills (Fowler, 2010). Currently, only two hypotheses provide testable, quantitative predictions about the morphometry of MSGLs with which we can compare our observations. These are the groove-ploughing (Tulaczyk *et al.*, 2001; Clark *et al.*, 2003) and the rilling instability hypotheses (Fowler, 2010). The former suggests that MSGLs are the product of 'groove-ploughing', formed by a series of ice keels at the sole of the glacier. The keels would develop when streaming ice encounters a topographically rough area upstream (i.e. outcropping bedrock) or through lateral compression as the ice stream narrows through a convergent onset zone. The ice keels would then plough into soft, saturated sediments downstream for many kilometres, thereby producing grooves defining the MSGLs (Tulaczyk *et al.*, 2001; Clark *et al.*, 2003). MSGL formation would thus be considered as primarily erosional, although some sediment squeezing and deposition would be likely to occur in the intervening ridges between adjacent keels.

Our work highlights three main issues for the groove-ploughing hypothesis to address. With the availability of higher resolution data it is apparent that individual MSGL initiate and terminate in various positions within an ice stream bed (Figure 7). This is instructive, as it implies that an individual MSGL can come into existence anywhere on the bed, contradicting the groove-ploughing expectations of the same ice keels surviving over very long distances (Tulaczyk *et al.*, 2001).

In relation to the previous point, a second issue for the groove-ploughing hypothesis relates to the unimodal distributions of MSGL metrics (Figure 4). With some exceptions (e.g. outcrops of bedding planes), bedrock roughness is usually uneven across an ice stream bed and keels (and MSGLs) should therefore form at variable sizes. Large differences might be expected between outcrops of rocks from different settings. However, results indicate that, for the most part, MSGL size is relatively similar across various ice stream beds with different underlying geology. The same argument applies to MSGL spacing. Uneven outcropping should generate unevenly spaced keels (and MSGLs). However, results show that MSGL spacing varies relatively little within (and between) ice stream beds.

A further testable prediction of the groove-ploughing hypothesis is that ice keels should reduce in size while moving downstream as they melt because of frictional heat. A reduction of the size of the keel would therefore imply that groove depth should shallow and the groove width should widen in a downstream direction, with a corresponding increase in the spacing between adjacent lineations. The studied MSGLs extend for tens of kilometres and cover considerable portions of the original ice stream beds (see section Datasets). However, results indicate that across-flow spacing either shows no statistically significant downstream trend or, with the exception of the Haldane palaeo ice stream bed,

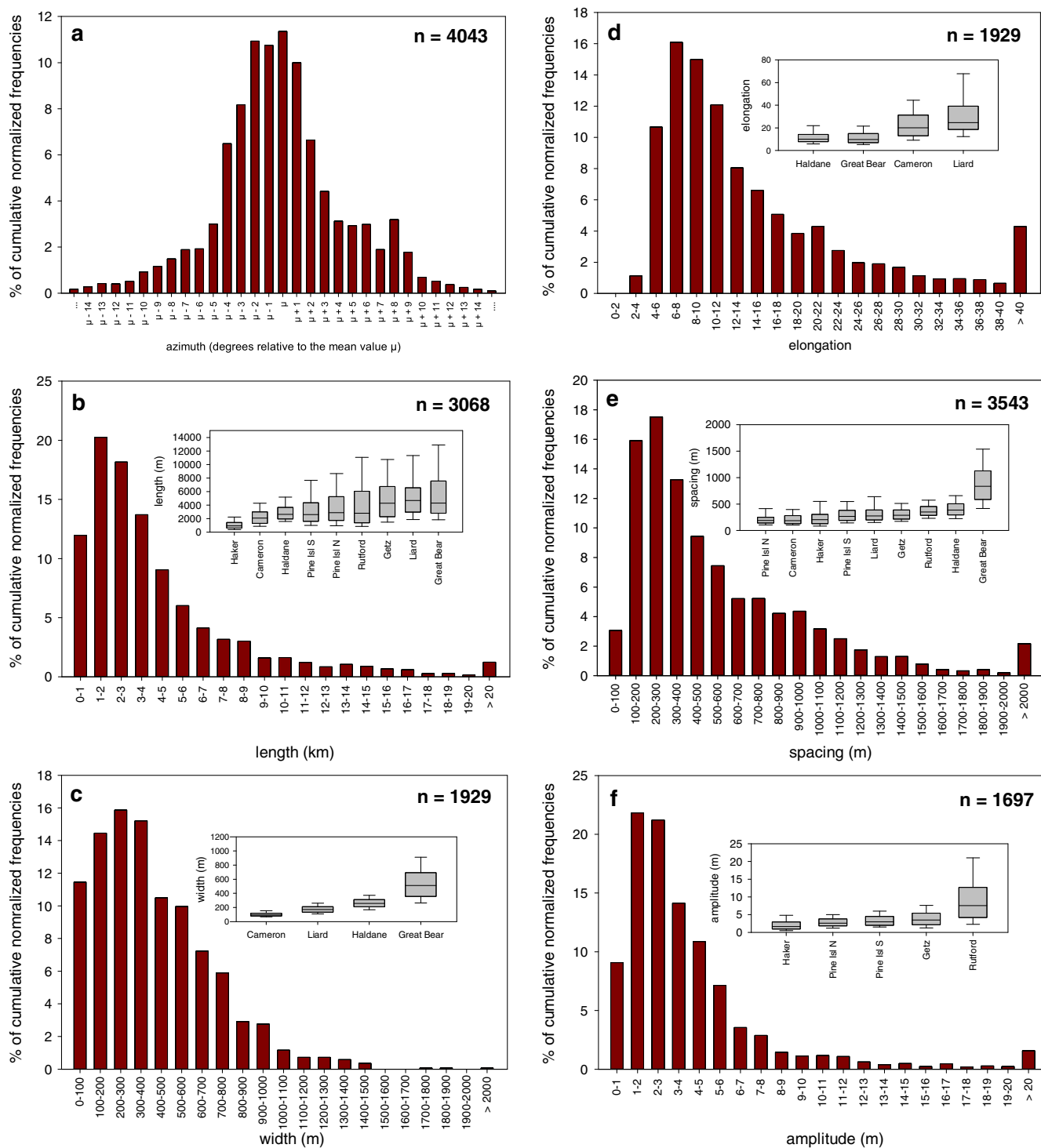


Figure 4. Frequency distribution of the azimuth (a), length (b), width (c), elongation (d), spacing (e) and amplitude (f) of all mapped MSGLs and statistical box plots for individual settings. The 5 percentile, 25 percentile, median, 75 percentile and 95 percentile are showed on the box plots. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

consistently decreases in a downstream direction (Getz, Pine Island N and Great Bear palaeo ice stream beds). For amplitude, different ice streams reveal different trends or no trend. Those showing MSGL amplitudes decreasing downstream (e.g. parts of the Rutford Ice Stream and the Getz palaeo ice stream bed) are consistent with the groove-ploughing prediction; while those characterized by no evident trend (e.g. Pine Island S) or amplitudes increasing downstream (e.g. Håkerringidupet and Pine Island N palaeo ice stream beds) are inconsistent. In its current form, therefore, the groove-ploughing hypothesis is mostly unable to account for our observations of MSGLs (see also Ó Cofaigh *et al.*, 2005).

The other hypothesis that provides quantitative predictions of the size and shape of MSGLs is that based on subglacial melt-water rilling (Fowler, 2010), which invokes an instability in an initially uniform water-film (typical value of 2.7 mm thick) flowing between the ice and the deformable subglacial till. Water-flow depth will be larger in an incipient stream, and this would allow faster flow and thus higher erosion and sediment transport. Consequently, the stream would deepen further, and this positive feedback, initiated by an instability, would result in the excavation of grooves, or rills, between ridges. The mathematical simulations suggest that the overlying ice would dampen the growth of the landform's height at relatively

Table III. Key statistics for MSCL azimuth, length, width, elongation, spacing and amplitude, summarized for each study area and for all areas (last column)

	PINE_IS_S	PINE_IS_N	GETZ	RUFFORD	HAKER	BEAR	CAMERON	LIARD	HALDANE	ALL
AZIMUTH (°N)	# MSCL	514	507	288	529	857	481	159	432	4043
	average	347	335	70	258	320	242	262	292	-
	standard deviation	3	8	4	9	9	3	2	4	-
	10 percentile	345	326	67	248	311	239	259	288	-
90 percentile	350	344	74	270	333	245	264	297	-	
LENGTH (m)	# MSCL	440	148	220	426	795	420	140	308	3068
	average	3651	5442	4331	1144	6160	2417	5616	3021	3967
	standard deviation	3371	4676	3904	831	5029	1632	3777	1551	3907
	10 percentile	1030	1500	840	364	2010	870	1920	1600	860
	mode	1000-2000	1000-2000	1000-2000	0-1000	3000-4000	1000-2000	4000-5000	2000-3000	1000-2000
	Median	2600	4280	2810	906	4420	2090	4690	2630	2750
90 percentile	7650	10610	10920	2215	12940	4260	11180	5170	8530	
max	23280	32650	17080	5553	37450	17860	17860	9320	37450	
WIDTH (m)	# MSCL	-	-	-	-	857	481	159	432	1929
	average	-	-	-	-	556	104	179	267	348
	standard deviation	-	-	-	-	273	40	60	85	271
	10 percentile	-	-	-	-	270	70	110	170	90
	mode	-	-	-	-	300-400	0-100	100-200	200-300	200-300
	Median	-	-	-	-	510	90	170	260	270
90 percentile	-	-	-	-	910	150	260	370	720	
max	-	-	-	-	2770	410	450	680	2770	
ELONGATION	# MSCL	-	-	-	-	857	481	159	432	1929
	average	-	-	-	-	12	24	33	12	17
	standard deviation	-	-	-	-	9	16	23	7	14
	10 percentile	-	-	-	-	5	9	12	6	6
	mode	-	-	-	-	6-8	12-14	20-22	8-10	6-8
	median	-	-	-	-	10	20	25	10	12
90 percentile	-	-	-	-	22	44	68	22	33	
max	-	-	-	-	90	125	134	45	134	
SPACING (m)	# MSCL	495	250	279	382	817	449	159	421	3543
	average	320	228	393	271	939	225	338	426	458
	10 percentile	140	110	230	90	420	100	150	230	140
	mode	200-300	100-200	300-400	100-200	700-800	100-200	200-300	300-400	200-300
	median	270	190	350	200	840	190	280	390	330
	90 percentile	540	410	560	540	1540	400	630	660	960
AMPLITUDE (m)	# MSCL	495	291	279	382	-	-	-	-	1697
	average	4	4	10	2	-	-	-	-	4
	10 percentile	2	1	2	1	-	-	-	-	1
	mode	2-3	1-2	4-5	1-2	-	-	-	-	1-2
	median	3	3	8	2	-	-	-	-	3
	90 percentile	6	8	20	5	-	-	-	-	9

Table IV. Regression analysis of spacing and amplitude trends downflow.

	PINE IS S	PINE IS N	GETZ	RUTFORD	HAKER	BEAR	CAMERON	LIARD	HALDANE
SPACING TREND									
distance considered (km)	38	31	35	38	33	144	50	51	42
slope of least squares fit-line	1.87	-2.77	-3.08	1.55	9.98	-2.12	0.77	-1.38	3.53
significance	0.0798	8.97×10^{-5}	0.0013	0.1583	0.0112	3.19×10^{-10}	0.1953	0.4181	0.0017
AMPLITUDE TREND									
distance considered (km)	38	31	35	38	33	-	-	-	-
slope of least squares fit-line	0.01	0.04	-0.05	0.07	0.13	-	-	-	-
significance	0.3785	1.20×10^{-6}	0.0005	0.0202	0.0016	-	-	-	-

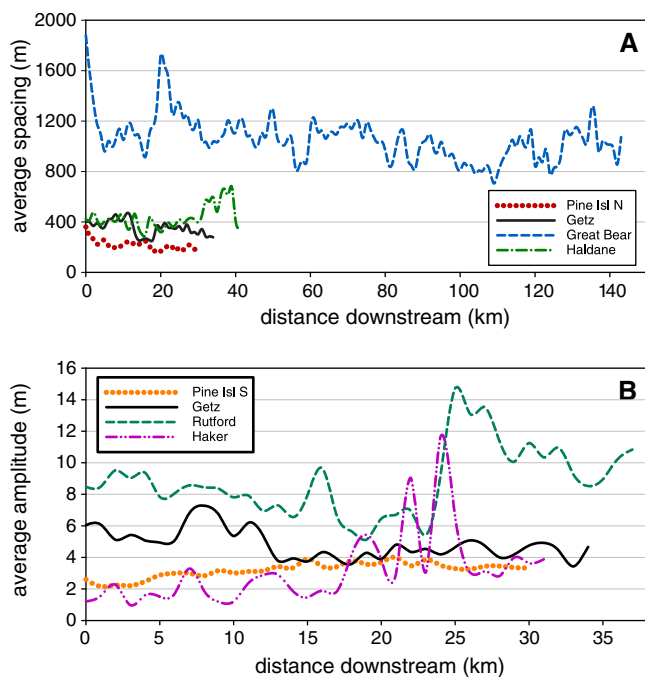


Figure 5. Downstream changes in MSGL mean spacing (A) and amplitude (B). Only settings showing statistically significant trends (as per Table IV) and/or discussed in the paper are shown. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

short wavelengths (12.3 m), while maximum (\sim most common) growth of the length and the width would occur at relatively long wavelengths (52.9 km and 394 m, respectively).

Our data show that most spacing values are between 200 and 300 m, with lengths between 1 and 2 km and amplitudes from 1 to 2 m. Thus, Fowler's (2010) predictions are overestimating both the length and amplitude of MSGLs, but the theoretical spacing is very close to observations and this hypothesis is yet to explore the full range of parameters. The hypothesis also suggests, implicitly, that MSGLs should be evenly spaced across an ice stream bed and this is indeed supported by the unimodal distribution of the across-flow spacing. A predominant spacing indicates that MSGLs tend to evenly occupy the available surface and could represent a spatially self-organized phenomenon, which is typical of instability-related bedforms (Clark, 2010). However, the data from this paper show that MSGLs initiate and terminate anywhere on the bed and this is not easily reconciled with rills forming where meltwater is expected to flow uninterrupted, unless changes in sediment properties are able to rapidly modify the character and pathway of meltwater flow on an ice stream.

In summary, an important implication of our quantitative data, therefore, is that current ideas and theories about MSGL formation are either un-supported or insufficiently developed (see also Stokes *et al.*, 2013). Since MSGLs tend to evolve into

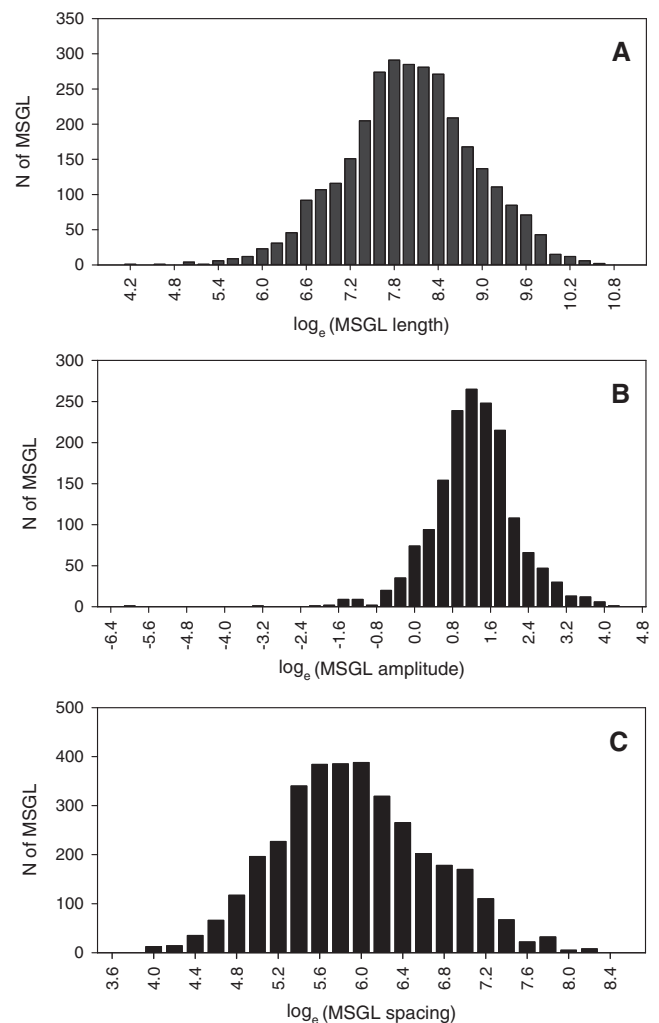


Figure 6. Log-normal frequency distribution of length (A), amplitude (B) and spacing (C).

a self-organized pattern (unimodal spacing distribution) and a dominant size and shape that is largely insensitive to local factors, it is plausible that some type of instability is governing their evolution, similarly to that which has been suggested for other glacial bedforms (Hindmarsh, 1998, 1999; Fowler, 2000). However, it is unclear at this stage if this would be the instability of the coupled ice and deforming bed invoked for drumlins, with MSGLs possibly representing elongate drumlins, or if it is an instability specific to the MSGL, such as the rilling one suggested by Fowler (2010), but which is not fully supported by the results presented in this paper.

MSGLs and ice stream flow mechanisms
Hydrological observations beneath the Whillans (B), Kamb (C) and Bindshadler (D) ice streams in Antarctica have suggested

that the basal water pressure is very close to the ice overburden pressure, implying that it is plausible for the ice to flow via sliding over its bed (Engelhardt and Kamb, 1997; Kamb, 2001). The formation of MSGs is compatible with ice stream sliding if these landforms are primarily formed by erosion, for example through a groove-ploughing mechanism (Tulaczyk *et al.*, 2001; Clark *et al.*, 2003) or in association with mega-floods (Shaw *et al.*, 2008). However, with regards to groove-ploughing, the results presented here indicate that predictions from this hypothesis are not fully supported by observations. Issues have also been raised in relation to the mega-flood theory (Ó Cofaigh *et al.*, 2005), among which that the volume of water required to form features occupying areas of thousands of square kms appears implausibly large (Ó Cofaigh *et al.*, 2010; Shaw and Young, 2010) and recent investigations have recorded MSGs being modified without any signs of concomitant mega-floods (King *et al.*, 2009), although strictly, this does not rule out floods having created them.

The notion that ice streams predominantly slide over their beds is, perhaps, also hard to reconcile with observations of trough mouth fans and grounding zone wedges deposited at ice stream grounding lines (Vorren and Laberg, 1997; Ó Cofaigh *et al.*, 2003), which have always been assumed to reflect high sediment transport rates and a strong coupling between the base of the ice and the underlying sediment. Unless erosion occurs independently from ice streaming (Christoffersen *et al.*, 2010) or an exceptional amount of (fine) sediment mobilization could be accounted for by the action of meltwater flowing in thin films, it is difficult to reconcile the deposition of large volumes of sediments with ice stream sliding. The alternative to sliding, which was traditionally advocated was that ice streams could largely (or entirely) move via subglacial sediment deformation, as supported by the discovery of several metres of fluted subglacial till with high porosity (i.e. likely to be dilated) beneath Whillans Ice Stream (Alley *et al.*, 1986). Further theoretical and observational constraints have indicated that rapid fluctuations in ice stream velocity (for instance those observed on the Whillans Ice Stream) are indeed associated with variation in shear strain rate of the subglacial till (Tulaczyk, 2006). Under the scenario of ice flow being facilitated by sediment deformation, the ice would be coupled to its bed and the basal till would essentially be transported downstream with the flow of the ice, helping explain the advection of large volumes of sediment towards the grounding line of ice streams. MSGs could evolve in this scenario either by net erosion or deposition or indeed both (redistribution of sediments). This is supported by observations of erosion and subsequent deposition beneath Rutford Ice Stream, where MSGs have been seen to evolve (King *et al.*, 2009; Smith and Murray, 2009); and by acoustic profiles that show MSGs being part of an acoustically semi-transparent unit interpreted as deformation till (Dowdeswell *et al.*, 2004). A further complication, however, is that recent studies have challenged the idea of a deep, pervasive, viscous shearing of the bed and observations from the Lake Michigan Lobe of the Laurentide Ice Sheet have suggested that the flow occurred there via shallow (decimetres) deformation of till patches (Thomason and Iverson, 2009; Iverson, 2010). Such a scenario is unlikely to promote spatially-continuous formation of MSGs over hundreds of square kilometres and would require a series of build-up events in order to generate metres-tall features. Furthermore, the internal structure of some MSGs has shown the presence of intact sedimentary bodies which are also hard to reconcile with pervasive deformation (Shaw *et al.*, 2000; Ó Cofaigh *et al.*, 2013). Taken together, these observations would suggest that MSGL formation takes place through a combination of sliding in the presence of near-overburden pressurized

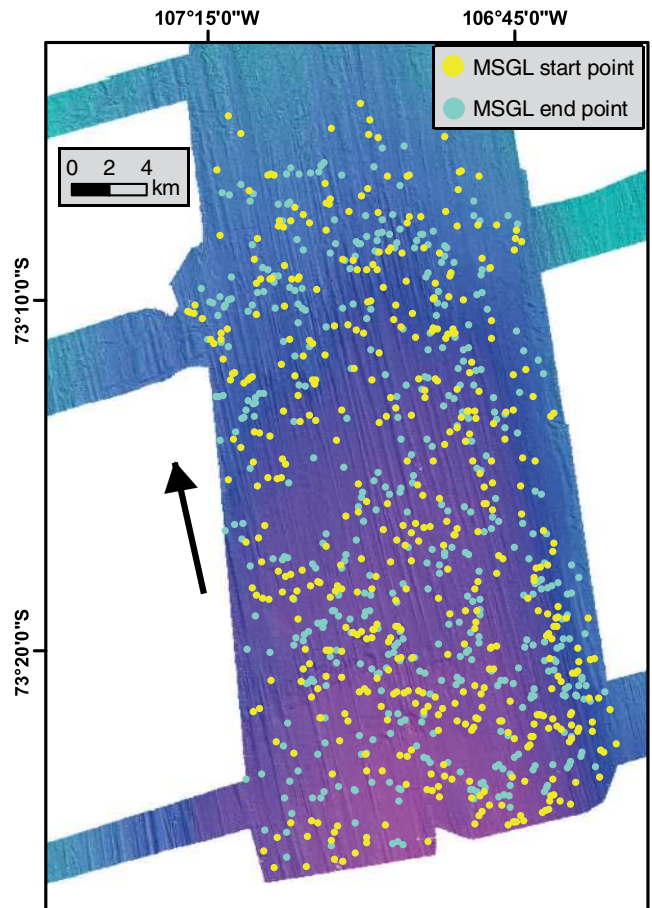


Figure 7. A map of the Pine Island S ice stream bed showing the location of MSGL start and end points as yellow and blue dots, respectively. The black arrow indicates the palaeo ice flow direction. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

basal meltwater, with some sediment excavated/deformed and advected from in between and along ridges. The rilling instability theory (Fowler, 2010) appears to include most of these elements. However, our observations are only partially supportive of the theory's predictions in its present form.

Conclusions

The ice–bed interface is a key control on fast ice flow, with associated impacts on ice sheet mass balance and sea level. This is where mega-scale glacial lineations are formed and their study is likely to improve our understanding of ice stream dynamics. A number of hypotheses have been developed to explain the formation of MSGs, but there is little agreement as to which might be correct, if any. In part, this reflects a lack of knowledge on their size, shape and spatial arrangement. This paper presents the first compilation of MSGL morphometries, allowing comparison between different ice stream beds, including both onshore and offshore, and palaeo and modern settings. Results suggest that MSGs can be described as subglacial landforms characterized by a combination of considerable size (i.e. kilometres), especially length, with very subtle amplitudes (i.e. metres). Arguably, the most important and distinctive characteristic is their spatial arrangement, i.e. their consistent spacing and striking parallel conformity. Morphometric similarities within and between various settings are a clear indication that MSGs are formed by the same mechanism, which is relatively insensitive to local conditions (topography, bedrock properties, etc.).

Of the ideas pertaining to the formation of MSGLs, only a few provide explicit predictions of their shape and size. The results presented here are difficult to reconcile with some aspects of the groove-ploughing theory (Tulaczyk *et al.*, 2001; Clark *et al.*, 2003). Rather, MSGLs appear to reflect a self-organized (consistent spacing), probably growing (log-normal distribution of their metrics) phenomenon that tends towards a dominant size and shape, which hints at some sort of instability among the most likely ingredients for the formation of MSGLs. Whether this is the rilling instability invoked by Fowler (2010), whose predictions are only partially compatible with our observations, or the till instability invoked for the formation of drumlins (Hindmarsh, 1999; Fowler, 2000) remains to be seen. However, the present work represents a quantitative foundation which can serve as a test for any future development of theories of MSGL formation and, more widely, on the nature and behaviour of the ice-bed interface.

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