Testing the groove-ploughing theory for mega-scale glacial lineaton (MSGL) formation, using a large dataset of their morphology

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Abstract

Subglacial bedforms provide an important insight into the nature of the processes operating at the ice-bed interface. In particular, the well-established link between mega-scale glacial lineations (MSGLs) and ice streams allows for indirect examination of the processes controlling the flow of ice streams, using observations of the morphology of features from palaeo-ice stream beds. Determining whether the existing theories of MSGL formation, in particular the groove-ploughing theory, can produce landforms with the morphology observed from palaeo-ice stream beds, is likely to have a significant impact on the understanding of the mechanisms that control the flow of ice streams.

A number of theories for MSGL formation have been proposed in the literature. There have, however, been relatively few attempts to falsify these theories. This is partially due to the limited amount of observational data, regarding MSGL morphology and internal composition. In particular, the groove-ploughing theory for MSGL formation provides a number of predictions which can be tested by examining the morphology of lineation populations. This work constitutes the first extensive test of the groove-ploughing theory, using a large dataset of MSGL morphology from a number of different palaeo-ice stream beds.

The objective of this work is to digitise a large sample of lineations, from three different palaeo-ice stream beds, in order to test the predictions of the groove-ploughing theory. It is necessary to identify the specific predictions that can realistically be tested using lineation morphology, and to devise measures that provide quantifiable tests of these predictions. Using the measures devised to test these predictions, along with close qualitative observation of other features of the palaeo-ice stream beds studied, it is found that the morphology of the lineations studied do not generally conform to the predictions of the groove-ploughing theory.

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1. Introduction

1.1. Ice Streams and Mega-Scale Glacial Lineations

Ice streams are rapidly moving, relatively narrow channels of ice bordered by slower moving ice. Typically flowing at rates of hundreds of metres per year, compared to surrounding sheet flow of metres per year or less, many ice streams are known to exist within the modern Antarctic and Greenland Ice Sheets (e.g. Bamber *et al*., 2000; Rignot and Mouginot, 2012). Furthemore, numerous palaeo-ice streams have been identified from formerly glaciated areas of North America (Stokes and Clark, 2001), Fennoscandinavia (Ottesen *et al.*, 2005a), the British Isles (Livingstone *et al.*, 2010), offshore of Antarctica (Ó Cofaigh *et al*., 2002) and offshore of Greenland (Evans *et al*., 2009).

Ice streams exert a major influence on ice sheet mass balance. For example, in Antarctica, ice streams account for ~90% of ice discharge despite comprising only ~10% of the surface area of the Antarctic Ice Sheet (Bentley and Giovinetto, 1991). Despite considerable research into the mechanisms that control ice stream discharge (e.g. Bamber *et al*., 2000; Pritchard *et al.*, 2009; Rignot *et al.*, 2011) they remain poorly understood, and a number of key questions such as the controls on initiation, shutdown and sediment properties are subjects of on-going debate.

The discovery of a relatively thick (several metres) till layer beneath the Whillans Ice Stream by Alley *et al*. (1986) and Engelhardt *et al*. (1990) led to the suggestion that deformation of saturated, low shear strength sediment can significantly contribute to ice stream velocity. The mechanics of sediment deformation and the relationship between the basal hydrology, basal sliding and sediment deformation, which allow the rapid flow of ice streams, are still poorly understood (e.g. Engelhardt and Kamb, 1998; Tulaczyk *et al*., 2001). That bedforms with very high elongation ratios form beneath ice sheets and ice streams has, however, been previously noted in the literature (e.g. Lemke, 1958; Clark, 1993). It is probable that examination of these bedforms will provide important insights into the conditions and processes occurring at the ice stream bed.

Understanding the subglacial processes that control ice stream flow is crucial in order determine the rate of ice, and sediment, discharge from modern ice sheets (Tulaczyk *et al.,* 2001). Bedforms formed by these subglacial processes provide one of the few (and certainly one of the most readily accessible) expressions of these processes that can be studied. Each of the number of theories that have been advanced to explain MSGL formation could have quite different implications on the way ice streams operate (Clark *et al*., 2003), and hence determining which formation theory is most likely to have occurred is very important to our understanding of ice stream dynamics.

Mega-scale glacial lineations (MSGLs) (examples of MSGLs are shown in Figure 1.1), are highly elongate ridges, with associated intervening grooves, that display large (of the order of 10^2-10^3 m) peak-to-peak spacing and low relief (Clark, 1993). A number of drumlinoid features with very high elongation ratios have been reported, from the bed of the former Laurentide Ice Sheet, by various authors, including Dean (1953), Lemke (1958) and Craig (1964). Classification of MSGLs as a separate landform class, however, was first made by Clark (1993), and MSGLs have since been reported, both in terrestrial and submarine environments, in many flowsets across many formerly glaciated regions (Stokes and Clark, 2001).

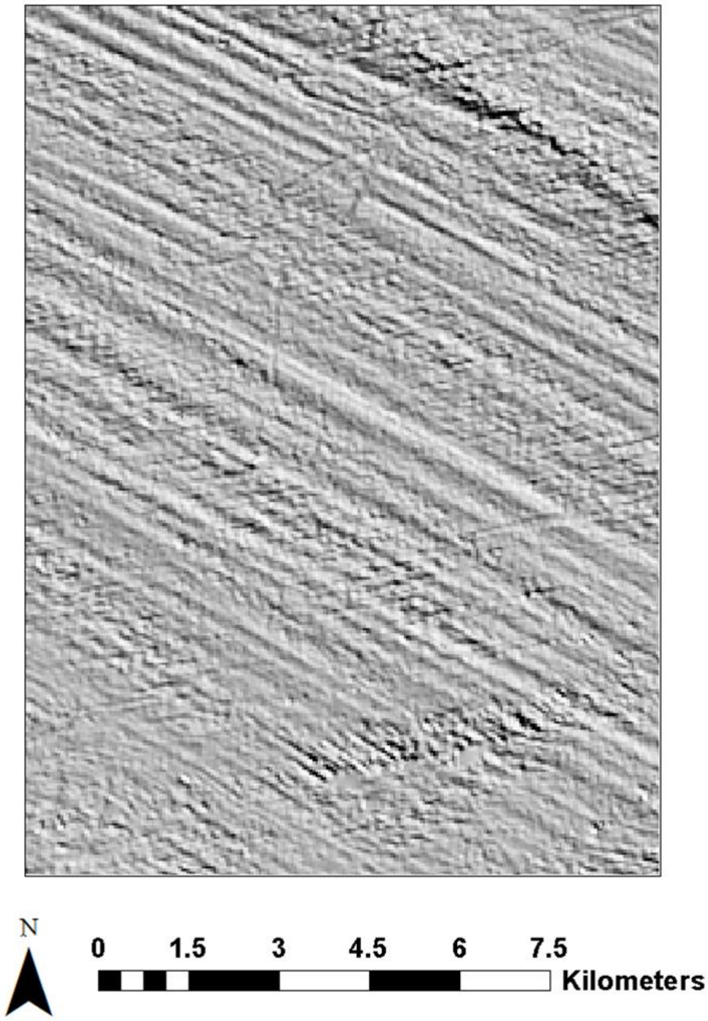

Figure 1.1: *Hillshade image of MSGLs from the bed of the Marguerite Bay palaeo-ice stream bed. Detailed morphological and sedimentological, work on this palaeo-ice stream flowset was carried out by Ó Cofaigh et al. (2002), Dowdeswell et al. (2004) and Ó Cofaigh et al., (2005).*

That MSGLs are closely associated with ice streams has been suggested on the basis of their extreme length and elongation (e.g. Clark, 1993; Stokes and Clark, 1999). MSGLs have also been observed on the bed of the Ross Sea directly in front of modern ice streams (e.g. Shipp *et al*., 1999). The appearance of the most elongate bedforms at the narrowest point along terrestrial ice stream flowsets (e.g. Stokes and Clark, 2003) and toward the terminus of marine ice stream flowsets (e.g. O'Cofaigh *et al*., 2002) has further indicated the close association between bedform elonagtion and fast ice flow.

Confirmation of the association of MSGLs with ice streams has come from recent seismic surveys of the bed of the Rutford Ice Stream (e.g. Smith *et al*., 2007; King *et al*., 2009). These surveys recorded lineations that are morphologically indistinguishable from those found on palaeo-ice stream beds (King *et al*., 2009). Another interesting observation from the geophysical surveys of King *et al*. (2009) was that lineations were being significantly modified, by erosion or deposition, on decadal time scales.

Although geophysical surveys of modern ice streams provide important insights into the behaviour of the deforming till layer beneath an ice stream, they have limited resolution and coverage. Palaeo-ice stream beds, however, provide a large sample of bedforms which can be readily mapped using existing remote sensing imagery and techniques. In many cases palaeo-ice stream beds also have the advantage that field examination of the composition and internal structure of bedforms is possible.

1.2. MSGL Morphology

As there is no widely accepted genetic classification system for glacial bedforms, landform morphology is the characteristic by which lineations are categorised (e.g. flutes, drumlins and MSGLs). Along with composition and distribution, morphology is one of the key aspects which any theory of MSGL formation must seek to explain. Detailed examination of lineation morphology is thus a potential method for constraining the current classification of these landforms in one group (under the term MSGLs) and, potentially, in the absence of equifinality, to a single formation process which produces this distinct lineation morphology.

Characterisation of lineation morphology generally uses a number of principal measures: lineation length, width, elongation ratio, lateral spacing and amplitude. It is notable, however, that the methods used to calculate these values can differ between studies (e.g. the methods used by Hillier and Smith (2012) to calculate lineation length are different to those used by Clark *et al*. (2009)). In general, all attempts to quantify lineation morphology must be influenced to some extent by pre-conceived notions of the planar shape of a typical lineation.

The nature of the relationship between MSGLs and less elongate bedform classes is one that has not been widely agreed upon in the literature (e.g. Rose, 1987; Clark, 1993; Stokes *et al.*, in prep). The scheme proposed by Clark (1993), on the basis of his observations (although this work did not involve empirical measurement of a large sample of lineations), was that the different bedform categories represented individual populations with minimal overlaps, as shown in Figure 1.2. The subglacial bedform continuum proposed by Rose (1987) provides an alternative view, suggesting that lineation length and spacing are continuously and unimodally distributed over the scale shown in Figure 1.2. These two hypotheses point to quite different views on the utility of classifying bedforms (as flutes, drumlins or MSGLs) and may have a significant bearing on the nature of MSGL formation.

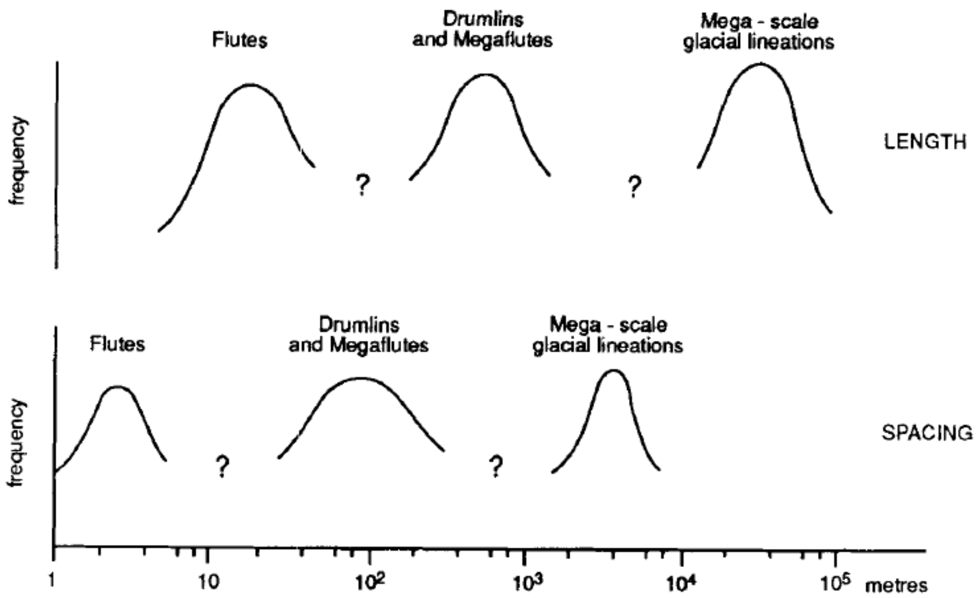

Figure 1.2: *Conceptual diagram showing one proposed morphological relationship between flutes, drumlins and MSGLs for lineation length and spacing. The relationship shown here suggests the bedform categories are separate and have clearly preferred lengths and spacings. From Clark (1993).*

Key criteria often cited in the literature (e.g. Stokes and Clark, 1999) for identification of bedforms comprising ice stream flowsets is an elongation ratio greater than 10:1 and length greater than a few kilometres. While many of these features have been categorised as MSGLs, there is no widely used threshold (in terms of either elongation ratio or length) between attenuated drumlins and

MSGLs. The judgement largely rests on characterisation of areas of the bed, with some shorter and less elongate lineations appearing within areas primarily composed of longer (MSGL) features (Stokes *et al.*, in prep).

Unlike other bedform categories, e.g. drumlins (Clark *et al*., 2009; Spagnolo *et al*., 2010), there have been no comprehensive quantitative studies of MSGL morphology. Typically quantitative reporting is restricted to a few ‘stand-alone’ values - most commonly length, width, spacing (or wavelength) and amplitude (or relief) - that the author(s) consider(s) representative of the entire MSGL field (see Tables 2.1, 2.2 and 2.3). The methodology used to obtain these values, whether they represent mean values from given areas/transects, or whether they are derived from a small number of single feature measurements is, in many cases, unclear.

1.3. MSGL Formation

The initial characterisation of MSGLs as a bedform class by Clark (1993) was accompanied by much discussion of the reasons why MSGLs are considerably more elongate than drumlins. The initial creation of the relief, often referred to as the ‘drumlin problem’ (Clark, 2010), is only briefly referred to by Clark (1993). Similarly, some of the MSGL formation theories proposed in the literature invoke processes unique to MSGL formation, whereas others propose extensions of processes that operate (at least in theory) to form drumlins but with greater ice velocity causing greater bedform elongation.

Since the first description of MSGLs, several formation theories have been proposed. Those that have been explored in detail are groove-ploughing (Clark *et al.*, 2003), catastrophic meltwater floods (Shaw *et al*., 2008) and an instability in a layer of deforming sediment (Fowler, 2010). Each of these theories proposes quite different formation mechanisms and each theory is at a different stage of development. The present study will focus primarily on testing of the morphological predictions of the groove-ploughing theory, although other theories will also be tested as far as is possible given the limited number of morphological predictions they make.

1.3.1. The Groove-Ploughing Theory

The groove-ploughing theory was first proposed by Clark *et al*. (2003) and suggests that large bumps in the ice base can act as 'keels' ploughing into the underlying sediment. This mechanism also suggests that MSGLs are primarily erosional features, although some squeezing of till on either side of an ice keel is likely to occur (Clark *et al*., 2003). Thus, instead of being considered as ridges with positive relief, MSGLs are in fact part of a grooved till surface. A major issue with this theory is whether an ice keel can avoid melt-out for a sufficient distance of movement downstream to allow MSGL formation. Although the survival of ice keels is a major consideration, and Clark *et al*. (2003) model the problem and discuss it in depth, it is not something that has been directly measured beneath a modern ice stream. Examination of lineation morphology, however, at least allows for comparison between theoretical ice keel melt-out and the shape of MSGL grooves and ridges.

The main reason that groove-ploughing is the primary focus of this work is that it provides a number of predictions regarding lineation morphology. This set of 10 predictions was created by Clark *et al*. (2003) as a means of possible future falsification of the groove-ploughing theory. In general, the other formation theories that will be discussed in this work do not have such a comprehensive set of predictions relating to landform morphology and hence cannot be so readily tested.

Although the predictions made by the groove-ploughing theory, as outlined by Clark *et al*. (2003), were designed to facilitate falsification of the theory, there has actually been very little work carried out to date that has tested these predictions. A major reason for this lack of testing of the predictions of the groove-ploughing theory is the lack of large datasets of MSGL morphology (as previously mentioned in Section 1.2). The present study aims to fill this gap by collecting morphological data from a large sample of lineations, from several different palaeo-ice streams, and then using this dataset to test the predictions of the groove-ploughing theory.

1.3.2. The Meltwater Megafloods Theory

The megaflood theory, proposed by Shaw *et al.* (2008) for MSGL, suggests that bedform formation occurs as a result of erosion during a subglacial megaflood event. The theory proposes that obstacles to the flow can set up paired vortices that preferentially erode other parts of the bed (Shaw *et al*., 2008).The megaflood theory has been the centre of much controversy, e.g., sediment composition of the bedforms (Evans *et al*., 2006) and potential for water storage (Clarke *et al*., 2005), in the literature.

The presence of crescentic scours around the stoss ends of bedforms has been suggested to be a result of flow separation, around an obstacle (i.e. the bedform), within the meltwater flow. Overdeepenings at the stoss ends of lineations have been observed from some locations, e.g. the Athabasca fluting field (Shaw *et al*., 2000), but it is unclear how common these features are. The present study will attempt to discover how common the presence of crescentic scours is on the palaeo-ice stream beds studied.

1.3.3. Bed Deformation and the Instability Theory

A number of related theories of bedform formation have been proposed that centre on sediment deformation at the bed. The proposal that the ice-bed interface is naturally unstable presents the possibility that drumlins could be formed without the need for pre-existing obstacles (Hindmarsh, 1998). Development of this theory to include feedback within the subglacial drainage has allowed Fowler (2010) to model a bedform forming instability and to calculate the preferred dimensions of lineations formed by this mechanism. The present study will collect a large amount of data on lineation morphology and will hence be able to test whether the lineations, from the areas mapped, fit in with the morphological values predicted by Fowler (2010).

1.4. Aims and Objectives

1.4.1. Aim

To test the groove-ploughing theory using the predictions made by Clark *et al*. (2003).

1.4.2. Objectives

1. To identify and map a large sample of MSGLs from three different palaeo-ice stream beds.

2. To measure the morphology of the sample collected in (1) including their length, width and elongation ratio.

3. To devise a number of novel measures, based on lineation morphology, to test the predictions of the groove-ploughing theory.

2. Literature Review

2.1. Introduction

Mega-scale glacial lineations (MSGLs) are highly elongate ridges, with associated intervening grooves, that have been widely associated with fast flowing ice streams (e.g. Clark, 1993). As previously mentioned, in Section 1.1, MSGLs have been reported from the beds of palaeo-ice streams of the Laurentide and Fennoscandian Ice Sheets (LIS and FIS, respectively) as well as offshore of the present Antarctic (Wellner *et al.*, 2006) and Greenland (Evans *et al.*, 2009) ice sheets. Recent geophysical observations of active MSGL formation on the bed of the Rutford Ice Stream (King *et al*., 2009) have provided further support for a link between MSGLs and ice streams.

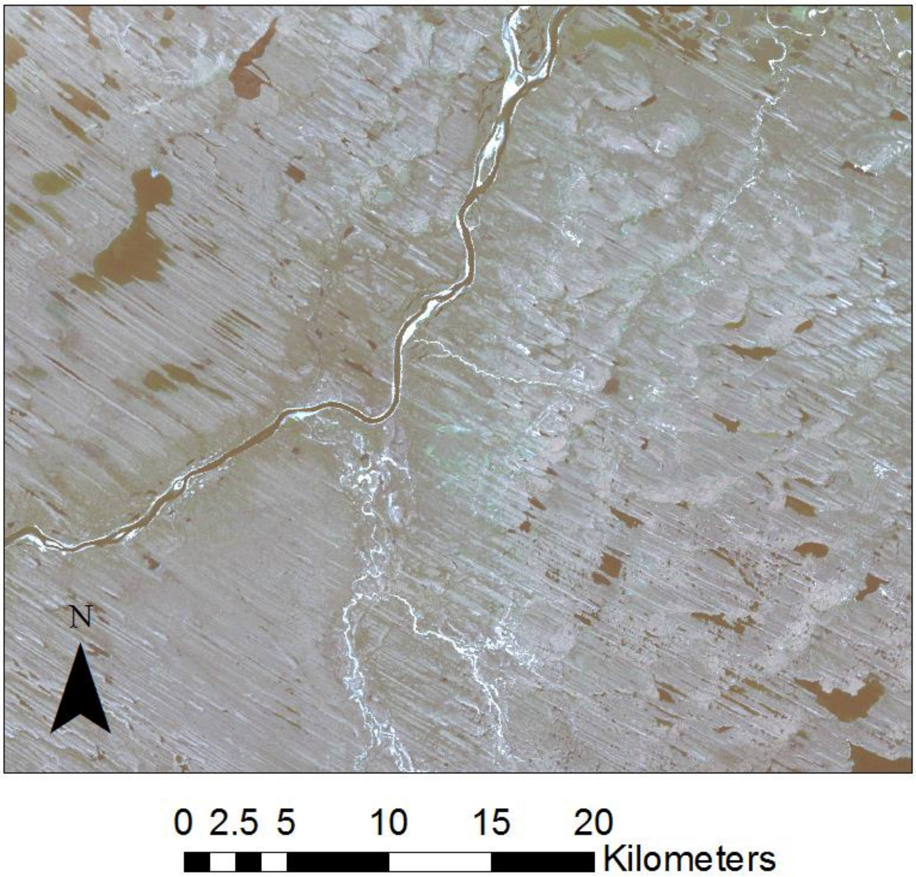

Figure 2.1: *Landsat ETM+ image (composite of bands 1, 2 and 3) of MSGLs in the trunk zone of the Dubawnt Lake palaeo-ice stream, Keewatin sector of the former LIS.*

The large spatial scale of MSGLs meant that they were not formally identified until after the advent of satellite remote sensing, when Clark (1993) identified flowsets of MSGLs on the bed of the former LIS. The term MSGL was introduced by Clark (1993) to suggest these bedforms are produced by ice moulding and are, potentially, a landform separate from the already well described flutes, drumlins and rogen moraine (Figure 1.2). An alternative proposal, the previously mentioned bedform continuum (see Section 1.2), suggests that lineation morphology varies continuously, and unimodally, across a range of scales (Aario, 1977; Rose, 1987).This relationship of MSGLs to other, less elongate, bedforms remains to be systematically tested, but may have a significant bearing on determining whether MSGLs are formed by a different process from other lineation classes.

The very high elongation ratios of MSGLs and their arrangement in fields has led various authors (e.g. Clark, 1993; Ó Cofaigh *et al*., 2002; Wellner *et al*., 2006) to suggest MSGLs to be formed exclusively under fast ice flow. The presence of MSGLs has thus been recognised as a key criterion for the identification of palaeo-ice streams (e.g. Stokes and Clark, 1999). This link to streaming flow has been confirmed by radar and seismic observations of MSGLs, as mentioned in Section 1.1, actively forming beneath the Rutford Ice Stream (King *et al*., 2009). As such, the study of MSGLs, and their formation, potentially provides an important insight into the processes occurring at ice stream beds (see Section 1.1).

Various theories of MSGL formation have been proposed, but there is little consensus within the literature as to which theory is most likely to be an accurate description of MSGL formation (presuming there is a single common MSGL formation mechanism). Much of the recent literature focuses on three main formation theories: the deforming bed instability theory (Hindmarsh, 1998), the groove-ploughing theory (Clark *et al*., 2003) and the subglacial megaflood theory (Shaw *et al*., 2008). These three theories, along with their variants (e.g. rilling instability theory (Fowler, 2010)), propose quite different mechanisms and may have very different consequences for the flow of ice streams. In the absence of equifinality, it may be possible to use parameters like MSGL morphology to test the proposed theories. Up until now, however, no systematic study of MSGLs, using large datasets of plan form morphometry, has been carried out.

This review aims to examine the morphological and sedimentological observations from reported MSGL fields, in order to find common features and to infer the range of observations which any formation theory must be capable of explaining. Consideration will be given to whether all features that meet the morphological definition of MSGLs can be treated as a single genetically related group, or whether they should be further subdivided. Mechanisms of MSGL formation that have been proposed in the literature will also be discussed and the extent to which they fit with the current range of observations examined.

2.2. MSGL Morphology

Landform morphology is the characteristic by which lineations are generally categorised (e.g. flutes, drumlins and MSGLs). Any successful formation theory must clearly be able to produce lineations with the range of morphologies observed from palaeo-ice stream beds. Detailed examination of morphology is thus potentially important in the testing of formation theories, provided that the theory provides some predictions regarding the expected morphology of the lineations formed by the proposed mechanism. This section will examine reported morphological values from the literature, and the few studies which provide more detailed observations of MSGL morphology and particularly morphological changes of MSGLs across a palaeo-ice stream bed.

While many features have been categorised as MSGLs (see Section 1.2), there is no widely used threshold to differentiate between drumlins and MSGLs. Their identification largely rests on characterisation of areas of the bed with some shorter and less elongate lineations appearing within areas mainly composed of longer features (Stokes *et al*., in prep). While many of the mega-scale glacial landforms identified thus far have relatively similar morphology to one another there remain several examples that have rather different morphology.

The first observations of mega-scale bedforms on the Antarctic continental shelf, reported by Canals *et al*. (2000) from the Gerlache-Boyd trough system, were of flow parallel features up to 100 km in length, 1-3 km wide and up to 40 m high. Described as ‘bundle’ structures by Canals *et al*. (2000), these features were suggested by these authors to be depositional landforms formed in subglacial till. Small numbers of similarly large flow parallel lineations are reported from the Norwegian Channel (lengths up to 200 km, 50 m in height and spacing of 20-30 km) with seismic observations again suggesting formation in till (Ottesen *et al*., 2005a). The dimensions of these features are considerably larger than those reported in the literature for the bulk of MSGLs (Tables 2.1, 2.2 and 2.3). It remains to be determined if these features are genetically related to the majority of reported MSGLs (if indeed the main population is a result of a single common formation process).

Megagrooves are a landform similar in scale to MSGLs that display only the negative expression of relief (Bradwell *et al*., 2008). If MSGLs have a primarily erosional formation mechanism, as suggested by the groove-ploughing theory (Clark *et al*., 2003), then it may be possible to produce grooves in stiffer substrates without remobilisation of till into intervening ridges (Clark *et al*., 2003). Observed megagrooves, however, are typically formed in bedrock: e.g. Assynt, Scotland (Bradwell *et al*., 2005) and Smith trough, Antarctic Peninsula (Heroy and Anderson, 2005). Bradwell *et al*. (2005) argue that the Assynt features are unlikely to have been eroded by ice keels due to fast rates of keel melt out on a bedrock substrate. A subglacial meltwater origin remains, however, a possibility (see Shaw *et al*., 2008), which could potentially genetically relate megagrooves and MSGLs.

2.2.1. MSGL dimensions as reported in the literature:

As already noted (Section 1.2), reporting of quantitative morphological data in the literature is relatively limited and often unsystematic. The reason for this is that these morphological values are commonly reported in order to give an example of the scale of the bedforms, while the primary purpose of most of these studies is not examination of MSGL morphology. The results of a review of the existing literature that present some quantative values for MSGL morphology is presented in Tables 2.1, 2.2 and 2.3.

Table 2.1: *Measures of MSGL morphology from literature concerned with Antarctic palaeo-ice streams. '(max.)' indicates values noted as maximum values. Mean values are reported where stated in the literature (i.e. mean values have not been independently calculated).*

Location	Paper	Length (km)	Width (km)	Amplitude (m)	Lateral Spacing (m)	Elongation ratio
N. AP Gerlache-Boyd Trough	Canals *et al.* (2003)	100	1-3	40	-	-
AP – Marguerite Trough	Dowdeswell *et al.* (2004)	10-17	0.13-0.4	2-6(±1)	-	-
AP – Marguerite Trough	Ó Cofaigh *et al.* (2002)	As above	As above	As above	-	30-90:1
AP- 6 Troughs (MSGLs in all but 1 (Smith Trough)).	Heroy and Anderson (2005)	>22 (max.)	-	10-20	200-600 mode= 300	>80:1 (max.)
S.AP- Belgica Trough	Ó Cofaigh *et al.* (2005)	9 (max.)	-	-	-	37:1
Pine island Bay (only mapped to mid-shelf)	Lowe and Anderson (2002)	7-20	0.13-0.25	15-30	300-500	-
Pine Island Bay (outer-shelf)	Evans et al. (2006)	3.5-6	0.14-0.18	-	-	18-60:1
Larsen/Robertson Trough	Evans *et al.* (2005)	5.69-11.2	0.1-0.4	-	-	16-40:1
Marguerite Trough	Ó Cofaigh *et al.* (2005)	10-22	0.15-0.55 (mean= 0.35)	2-8(±1) (mean=3)	-	-
Amundsen Sea-Dotson and Getz (A and B) troughs.	Larter *et al.* (2009)	-	-	-	-	40:1 (max.)
Amundsen Sea Embayment	Graham *et al.* (2009)	6-38	0.13-0.45	2-18	80-300	25-140:1
Pine Island Glacier	Graham *et al.* (2010)	4-16	0.25-0.5	2-6	-	64:1
South Georgia-several offshore troughs	Graham *et al.* (2008)	0.4-10	0.25-0.5	20 (max.)	-	24:1 (max.)
Review of many WAIS troughs	Wellner *et al.* (2006)	-	-	2-20	200-600	-
Ross Sea	Shipp *et al.* (1999)	20	-	-	300-650	-
Pine Island Trough	Jakobsson *et al.* (2011)	-	-	-	150-500	-
Gerlache-Boyd Trough	Canals *et al.* (2000)	100 (max.)	1-3	40	-	-

Table 2.2: *Measures of MSGL morphology from literature concerned with Arctic palaeo-ice streams. '(max.)' indicates values noted as maximum values. Mean values are reported where stated in the literature (i.e. mean values have not been independently calculated).*

Location	**Paper**	**Length (km)**	**Width (km)**	**Amplitude (m)**	**Lateral Spacing (m)**	**Elongation Ratio**
NE Greenland (Westwind Trough)	Evans *et al.* (2009)	2.5-10	0.2-0.34	-	-	12-33:1
Svalbard (Bore-bukta)	Ottesen and Dowdeswell, (2006)	2.5 (max.)	0.02-0.1	10 (max.)	-	-
Norwegian shelf- about 20 troughs	Ottesen *et al.* (2005)	4-15 (One trough- Barents Sea= 35)	0.15-0.5 (Barents Sea= 3)	2-25	100-800 (Barents Sea= 3700)	-
Vestfjorden-Traenadjupet system (N.Norway)	Ottesen *et al.* (2005)	-	-	5-10	300-700	-
N.Norway- several troughs	Ottesen *et al.* (2008)	3-40	0.2-1.2	1-30	250-3000	>10:1
S. Barents Sea- several troughs	Winsborrow *et al.* (2010)	20-180	1-5	7	-	-
Outer Bear Island trough, W. Barents Sea	Andreassen *et al.* (2004)	38 (max.)	0.05-0.36	10 (max.)	-	105:1 (max.)
SW. Barents Sea (several troughs feeding into Bjornoyrenna trough).	Andreassen *et al.* (2008)	120-180	0.5-5	4-10	-	33-85:1
N. and W. Svalbard- various troughs	Ottesen *et al.* (2007)	10 (max.)	-	15 (max.)	100-2000	-
Norwegian Channel	Sejrup *et al.* (2003)	-	0.15-0.4	0.1-15	300	-
NW Barents Sea- Kveithola trough	Rebesco *et al.* (2011)	8 (max.)	0.1-0.6	15 (max.)	-	-

Table 2.3: *Measures of MSGL morphology from literature concerned with LIS palaeo-ice streams. '(max.)' indicates values noted as maximum values. Mean values are reported where stated in the literature (i.e. mean values have not been independently calculated).*

Location	**Paper**	**Length (km)**	**Width (km)**	**Amplitude (m)**	**Lateral Spacing (m)**	**Elongation Ratio**
W.Canadian Prairies- 5 cross-cutting ice streams	Ó Cofaigh *et al.* (2010)	15->65	-	-	-	-
Dubawnt Lake	Stokes and Clark (2002)	12.248 (max.) mean=4	0.2-0.4	-	-	14-48:1
Keewatin (including Dubawnt Lake flowset)	Greenwood and Kleman (2010)	35.9 (max.) mean=9.5	-	-	-	30.8:1 (max.) mean= 10.2:1
Arctic Ocean	Polyak *et al.* (2001)	15 (max.)	-	-	50-200	-
Athabasca, Alberta	Shaw *et al.* (2000)	15 (max.)	0.1-0.2	15	-	100:1 (max.)
Victoria Island/Amundsen Gulf	Stokes *et al.* (2006)	40 (max.)	-	-	-	-
Central Canada	Ross *et al.* (2009)	80 (max.)	-	-	-	-
Blackspring ridge, S.Alberta	Munro-Stasiuk and Shaw (2002)	5-15	0.1-0.5	10-20	-	10-100:1
M'Clintock Channel, Victoria Island	Clark and Stokes (2001)	20 (max.) mean= 1.85	-	10-50	150-2000 mean= 620	8-30:1
Labrador sector (SE. of Keewatin sector)	Clark *et al.* (2000)	>100 (max.)	-	-	-	-
Several LIS flowsets- not stated specifically	Clark (1993)	8-70	0.2-1.3	-	300-5000	-

Lateral spacing of lineations is one of the values that help to quantify the scale of the 'roughness' of the bed related to MSGLs. The most extreme values of spacing reported in the literature are 20 m (Ottesen and Dowdeswell, 2006) and 5 km (Clark, 1993). Spacing of MSGLs from the beds of various submarine troughs on the Antarctic continental shelf were reported by Heroy and Anderson (2005) who produce a histogram, using a total of 95 observations from troughs in 4 different regions (Figure 2.2), with the mid-point of the modal class equal to 300 m and most observations within the 200-600 m range. These values broadly concur with other reported values from Antarctic troughs (e.g. Graham *et al*., 2009; Ó Cofaigh *et al*., 2005; Jakobsson *et al*., 2011) with the exception of the 'bundle structures' reported by Canals *et al*. (2000), from the Gerlache-Boyd trough, which have spacing in the range 1-5 km (Heroy and Anderson, 2005). This similarity in spacing values is viewed by Heroy and Anderson (2005) to represent a morphological class which is genetically different from those reported from the Northern Hemisphere.

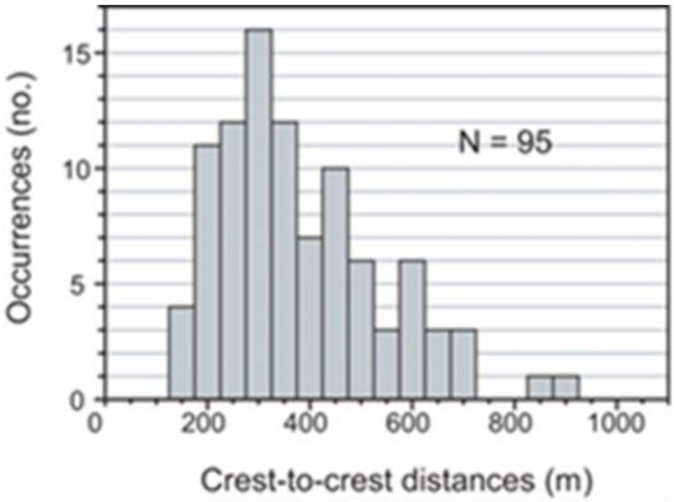

Figure 2.2: *Histogram of crest-to-crest spacings of MSGLs from various Antarctic troughs. From Heroy and Anderson (2005).*

Spacing values for MSGLs from a large sample of troughs (approximately 20) on the continental shelf of Norway, reported by Ottesen *et al*. (2005a), also have values typically in the range 200-600 m. These values broadly concur with other reports from the troughs offshore of the former FIS (e.g. Ottesen *et al*., 2005b and Ottesen *et al*., 2008). However, smaller spacing values have been reported from Svalbard, 20-100 m (Ottesen and Dowdeswell, 2006). Similarity in spacing values from troughs offshore of Antarctica and Norway, excepting a few outliers, potentially discredits the Heroy and Anderson (2005) idea that Antarctic MSGLs are a unique population and perhaps instead shows a feature common to topographically constrained ice streams. The only reported spacing values from the LIS, 0.3-5 km for various MSGL fields (Clark, 1993) and 150-2000 m for the M'Clintock Channel Ice Stream (Clark and Stokes, 2001) suggests that spacing values may be considerably more varied here.

Maximum MSGL length in many studies is below 20 km. However, there are several reports of considerably longer features, e.g. 180 km for the Djuprenna trough (Andreasson *et al*., 2008). The amplitude of MSGLs is a parameter recorded primarily by studies of marine troughs; largely due to the relatively high vertical resolution of sonar data. The maximum value reported for the majority of troughs is less than 20 m, while reports of features regularly exceeding 10 m are rare (Tables 2.1, 2.2 and 2.3). Elongation ratio appears to vary quite widely with several reports of maximum values exceeding 100:1 (e.g. Shaw, 2000; Andreasson *et al*., 2004), but are more typically reported in the range 10-100:1.

2.2.2. Within field change in MSGL morphology

Changes in MSGL morphology across palaeo-ice stream beds shows how processes vary with distance downstream, and with relation to the lateral ice stream margins. Changes in morphology, particularly elongation ratio across palaeo-ice stream beds, has been used (e.g. Stokes and Clark 2002) to draw inferences about flow patterns within palaeo-ice streams. In particular, the groove-ploughing formation theory makes predictions of changes in MSGL spacing and amplitude (Clark *et al*., 2003) that can be tested by making measurements of these values across the area of palaeo-ice stream beds.

The Dubawnt Lake flowset, studied by Stokes and Clark (2002), was found to display a peak in mean lineation elongation ratio in a main trunk zone, located downflow of a zone of convergent bedforms and upflow of a lobate terminus zone. The peak in mean lineation length coincides with the main trunk zone, while mean width peaks somewhat upflow of this (Stokes and Clark, 2002). This increase in elongation combined with bedform convergence is suggested (Stokes and Clark, 2003) to represent an ice velocity peak, Figure 2.3. Transverse to ice flow, the mean elongation ratio, length and width of bedforms were all found to increase toward the centre of the Dubawnt Lake flowset (Stokes and Clark, 2003).

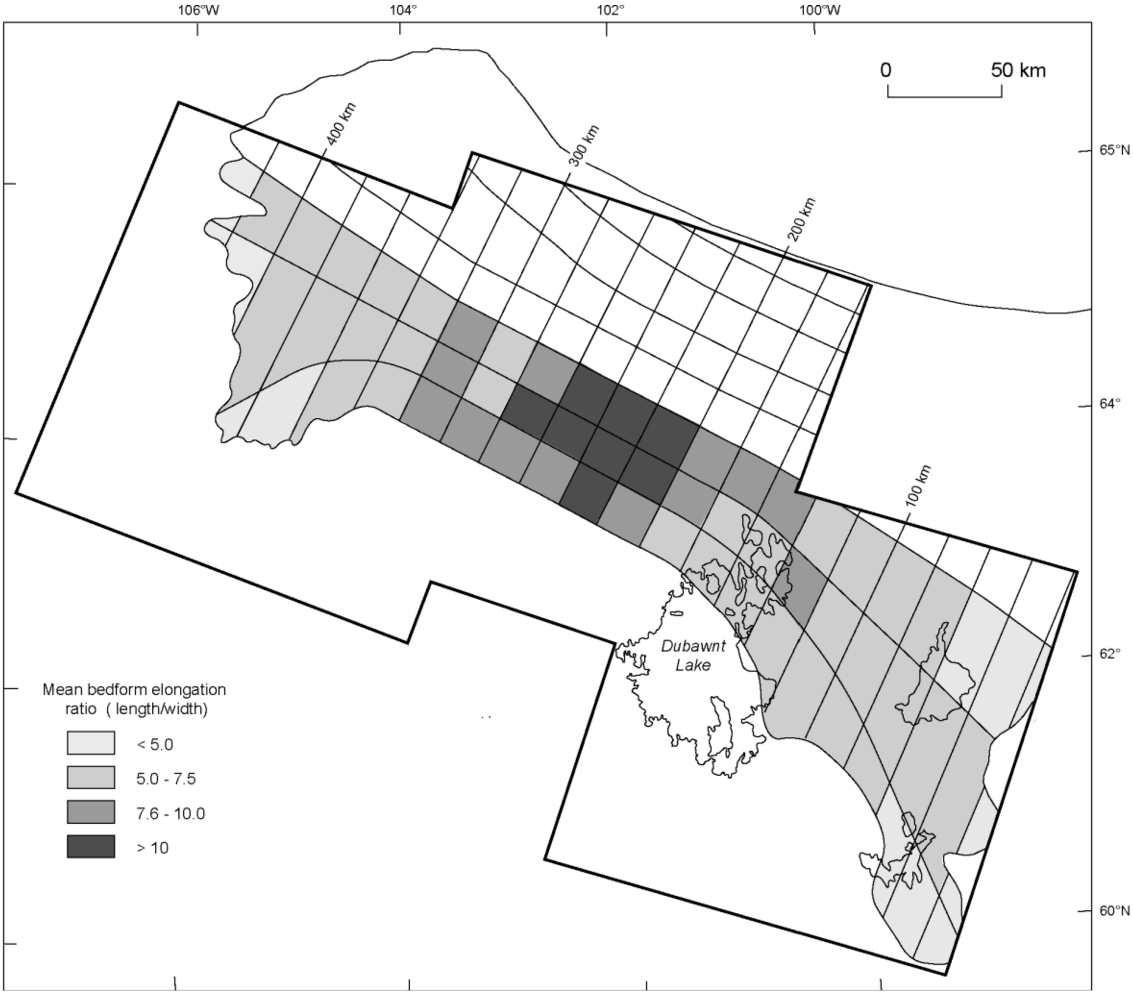

Figure 2.3: *Bedform elongation ratio across the southern part of the Dubawnt Lake palaeo-ice stream. Peak elongation is found in the 'trunk' zone of the ice stream presumably corresponding with an ice velocity peak. From Stokes and Clark, (2002).*

In contrast to the non-topographically controlled and terrestrially terminating Dubawnt Lake flowset, Graham *et al*. (2009) report gradual elongation ratio increase downstream, to the edge of the continental shelf, for lineations within a marine trough in the Amundsen Sea (Figure 2.4). While maximum elongation ratio does, indeed, appear to increase downstream, it is notable that a number of less elongate lineations are present, even near the downstream end of the lineations measured. It is also notable that the three classifications used for bedforms in Figure 2.4 (MSGLs, Lineations and Drumlins) have considerable numbers of overlapping elongation ratio values.

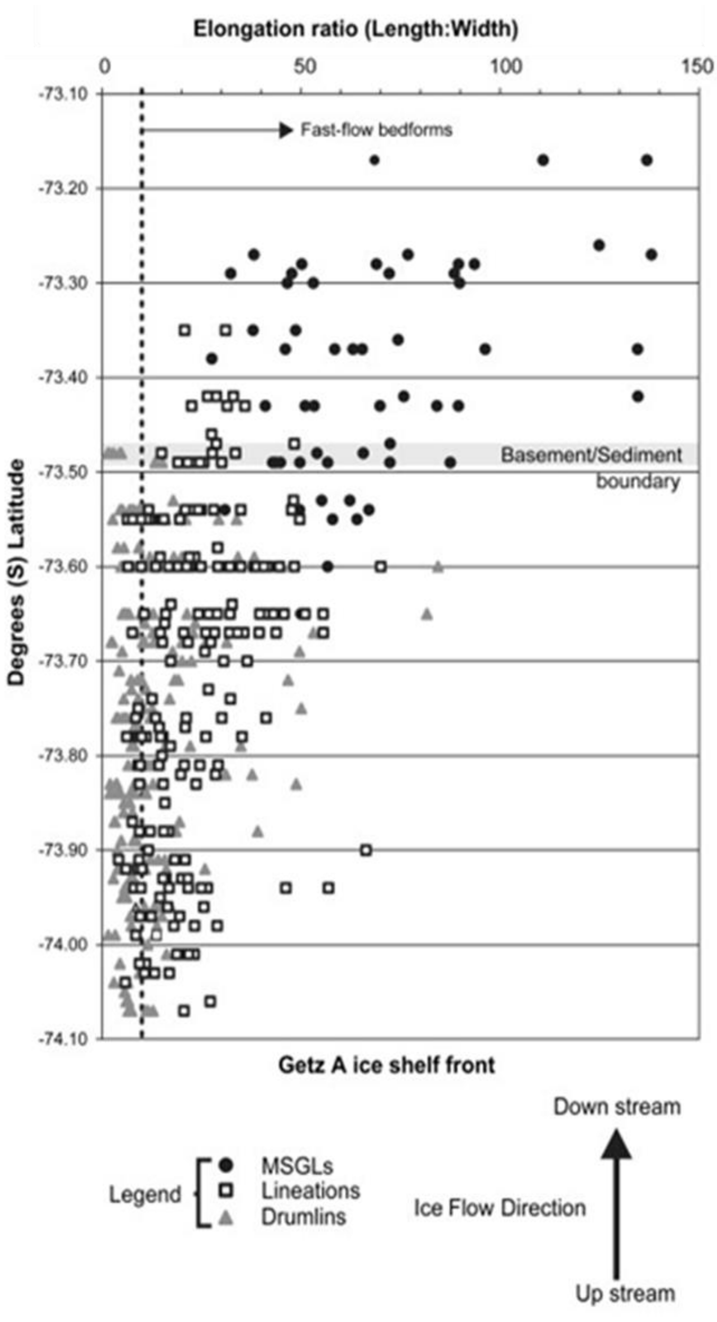

Figure 2.4: *Elongation ratio of bedforms from a trough in the Amundsen Sea Embayment. Note that elongation ratio increases to the shelf edge and that there is considerable overlap in elongation ratio between those features classified as MSGLs and lineations/drumlins. From Graham et al. (2009).*

Downflow decrease in MSGL spacing and amplitude was noted by Clark *et al*. (2003) to be a key prediction of the groove-ploughing theory. Observational testing of this prediction in Clark *et al*. (2003) used a number of extracted profiles from the ‘bundle’ structures of the Gerlache-Boyd Trough (Canals *et al*., 2000). Extracted transects showed general reduction in both amplitude and spacing downstream (Clark *et al*., 2003). The small number of profiles used and the already discussed morphological differences between these ‘bundles’ and other observed MSGLs, however, probably limits the effectiveness of this test. Use of extracted transects from the Marguerite Trough (Ó Cofaigh *et al*., 2005), found that lineation amplitude remains constant downflow and mean wavelength shows only a slight decrease. At present, given the small number of MSGLs measured at relatively few transects and the use of only two palaeo-ice stream beds, it is not possible to evaluate this prediction thoroughly.

2.2.3. Other Observations of MSGL Morphology

Bifurcation and merging of MSGLs has been observed for a small number of lineations within the Marguerite Trough by Ó Cofaigh *et al*. (2005). Although MSGLs have been reported to diverge around islands in some Norwegian troughs (Ottesen *et al*., 2005) and crosscutting of MSGLs is a widely observed phenomenon (e.g. Wellner *et al*., 2006) observation of true bifurcation of MSGLs is, potentially, very rare. Such bifurcation is potentially a characteristic that would be hard to account for within the framework of many formation theories, including groove-ploughing (Ó Cofaigh *et al*., 2005), although how widespread this observation is, is currently impossible to gauge. Another observation from Marguerite trough is the discovery of small flat areas of the bed, interpreted as ‘seeding points’ by Ó Cofaigh *et al*. (2005), immediately upflow of MSGL ridge initiation points.

The prevalent view of MSGLs as straight, uniform, bedforms has been challenged by observations (Munro-Stasiuk and Shaw, 2002) of a small number of features within the Athabasca fluting field with hook-like morphology, Figure 2.5. These hook-like features are noted by Munro-Stasiuk and Shaw (2002) as generally being shorter and less elongate landforms. A further observation from the Athabasca fluting field, suggested as being more widespread, are parabolic depressions, see the example shown in Figure 2.5, around the upstream ends of the lineations. Although there are limited reports of similar scours elsewhere, e.g. Marguerite Bay (Ó Cofaigh *et al*., 2005), it remains to be seen how common these features are.

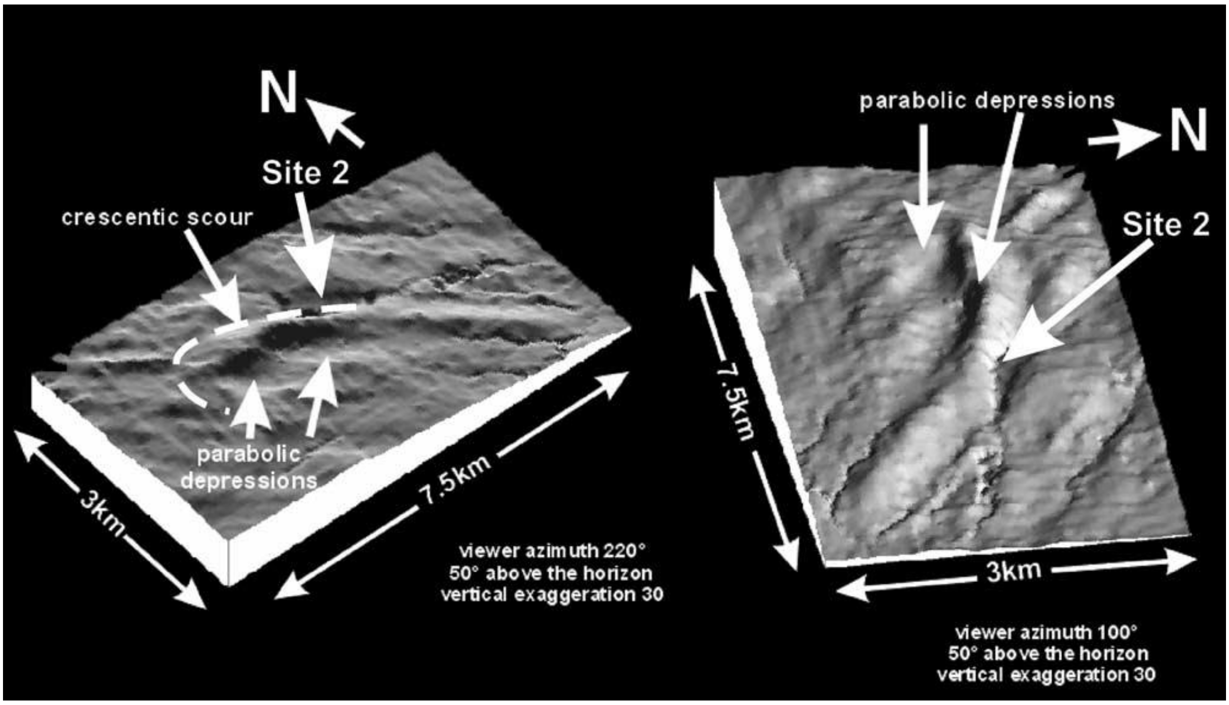

Figure 2.5: *Extracts from DEMs, with different viewer azimuths, showing a lineation with what appears to be a hook-like morphology, from Munro-Stasiuk and Shaw (2002). Munro-Stasiuk and Shaw (2002) attribute this type of feature to flow separation within a fluid flow.*

2.3. MSGL composition and internal structure

The sediment composition and internal structure of MSGLs potentially represent key clues to landform formation, as well as potential differences within the landform population. The sedimentary structure of various different MSGL fields has been reported in a number of papers (e.g. Shaw *et al*, 2000; Evans *et al*., 2008; Ó Cofaigh *et al*., 2010). The limited resolution associated with acoustic stratigraphy, and limited large clast recovery of the (typically) small numbers of sediment cores taken, however, mean that data from marine troughs is limited in resolution and quality. Detailed examination of terrestrial MSGL fields is also relatively limited, partially because of limited section availability related to the very low amplitude of MSGLs, and inability to identify MSGLs in the field. Due to the different capabilities of the techniques used to investigate MSGLs this section will review marine and terrestrial MSGLs separately.

2.3.1. Marine MSGL

The MSGLs in the Antarctic troughs are generally formed in the upper surface of a massive, matrix supported and low shear strength diamict (e.g. Dowdeswell *et al*., 2004; Heroy and Anderson, 2005; Ó Cofaigh *et al*., 2005). This diamict, widely reported as an acoustically transparent layer, commonly unconformably overlies another higher shear strength diamict (Ó Cofaigh *et al*., 2007). These two diamictons will be referred to as the 'soft' and 'stiff' diamictons, respectively (after Ó Cofaigh *et al*., 2007). The sediment sequence is generally capped by at least one relatively thin glacimarine unit (e.g. Heroy and Anderson, 2005). In terms of lateral sediment distribution, Ó Cofaigh *et al*. (2007), reviewing the Belgica, Robertson, Pine Island and Marguerite Troughs, report the soft diamict only from within the outer troughs, whereas the stiff diamict was also found across the adjacent shallow highs. The soft diamict appears to be variable in depth, within and between individual troughs, with reports of a minimum of as little as 1 m for the troughs reviewed by Ó Cofaigh *et al*. (2007), and a maximum of 20 m for troughs in the eastern Ross Sea (Mosola and Anderson, 2006).

Coring of the soft diamict reveals it to be matrix-supported with varying concentrations of small, poorly sorted, often striated and generally sub-angular clasts (Evans *et al*., 2005). The matrix of the soft diamict is composed of a silty/clayey mud (Evans *et al*., 2005; Ó Cofaigh *et al*., 2007). Although commonly reported as being structureless at the macro-scale (e.g. Dowdeswell *et al*., 2004) x-radiographs on samples from Marguerite Bay (Ó Cofaigh *et al*., 2005) reveal occasional sub-horizontal shear planes and associated aligned clasts. The lower stiff diamict has very similar composition, although Ó Cofaigh *et al*. (2005) report a lower percentage of clay than the soft diamict, and macro-scale features (Ó Cofaigh *et al*., 2007). The diamictons are also similar in terms of mineralogical composition as determined by gamma ray and magnetic susceptibility characteristics (Mosola and Anderson, 2006). Analysis of the micromorphology of both diamictons (Ó Cofaigh *et al*., 2005) reveals shear planes, plasmic fabrics and rotational structures interpreted as evidence for subglacial shear.

The contact between the soft and stiff diamicts ranges between sharp and gradational (Evans *et al*., 2005), as does the change in shear strength and porosity (Ó Cofaigh *et al*., 2007). Occasionally, interlayering of the two diamictons occurs. In a single core from Marguerite Bay (Ó Cofaigh *et al*., 2007), an intervening thin unit (7 cm) of massive, sheared, clayey mud separates the soft and stiff diamicts. This unit is interpreted by Ó Cofaigh *et a*l. (2007) as representing a period of subaqueous deposition between the emplacement of the two diamictons.

A feature reported in several studies (e.g. Evans *et al*., 2005, 2006; Ó Cofaigh *et al*., 2005) is irregularity of the basal reflector, detected by acoustics, which separates the soft and stiff diamicts. This irregularity of the basal reflector is reported by Evans *et al*. (2006) to be hummocky in nature in some areas and grooved in others. The association with grooves led Evans *et al*. (2006) to suggest that these features were evidence of groove-ploughing operating underneath a palaeo-ice stream, which may potentially support groove-ploughing as a possible MSGL formation method. Grooving of the basal reflector is, however, far from ubiquitous in troughs with MSGLs, and Ó Cofaigh *et al*. (2005) observe that while grooving is present in one area of the Marguerite trough, it is a different wavelength to the MSGLs.

Both the soft and stiff diamictons have been widely interpreted as tills (e.g. Dowdeswell *et al*., 2004; Mosola and Anderson, 2006; Evans *et al*., 2006), most likely hybrids formed by a combination of subglacial deformation and lodgement (e.g. Ó Cofaigh *et al*., 2005, 2007). Similarities in the composition of the tills, particularly pebble lithology, have led to the suggestion (Ó Cofaigh *et al*., 2007) that the soft diamict is derived from reworking of the underlying stiff diamict.

Detailed examination of the soft diamict through extraction of cores has been carried out by a number of studies (e.g. Lowe and Anderson, 2002; Dowdeswell *et al*., 2004; Heroy and Anderson, 2005). However, the problem of cores being unable to retrieve large clasts may lead to erroneous conclusions regarding the nature of this sediment. Heroy and Anderson (2005), for example, report sub-angular pebbles to small cobbles from coring of the soft diamict which approach the diameter of their cores. Use of acoustic sounding techniques, however, allows for the detection of the soft diamict while generally being unable to penetrate the basal reflector separating it from the lower stiff diamict which requires retrieval by coring (Dowdeswell *et al*., 2004).

2.3.2. Terrestrially exposed MSGLs

Studying terrestrial MSGLs has the advantage of being able to directly examine sediment sections rather than relying on point data from coring or acoustic data that is relatively limited in terms of detailed examination of sedimentology. The limited number and quality of exposures (a particular problem in low relief areas like palaeo-ice stream beds) means, however, that information on composition and sedimentary structure of MSGLs is still drawn from a small number of sites. The relatively few reports in the literature which do focus on terrestrial MSGL composition are all from the bed of the former LIS.

Composition of lineations within palaeo-ice streams in Alberta, often referred to as flutes or megaflutes but with dimensions frequently conforming to the MSGL category, has been examined in a number of papers and remains a source of debate in the literature (e.g. Shaw *et al*., 2000; Evans *et al*., 2008). Evans *et al*. (2008) report two corridors of streamlined terrain (the West and Central Alberta Ice Streams), containing numerous lineations, with a thin till veneer at the centre of the corridor contrasting with thick stacked till sequences at the ice stream terminus. The interpretation of these corridors of smoothed terrain, differing between palaeo-ice stream bed (Evans *et al*., 2008) and mega-flood pathway (Shaw, 2010), is based largely on the sediment composition of the lineation flowsets.

Observations from the Athabasca fluting field (Shaw *et al*., 2000), within the track of the feature referred to by Evans *et al*. (2008) as the Western Alberta Ice Stream (and later as the High Plains Ice Stream), show a sequence of interbedded diamictons below a deposit interpreted as a boulder lag. Shaw *et al*. (2000) argue against pervasive deformation at this site because of preserved intra-till deposits and boulder pavements and instead prefer deposition by melt-out. The Blackspring ridge fluting field, also within the Western Alberta/High Plains Ice Stream, was investigated by Munro-Stasiuk and Shaw (2002) who found its ridges to be composed of sorted, well rounded, cobbles and gravels which they interpret as being fluvial in origin. Evans *et al*. (2006) suggest, however, that Munro-Stasiuk and Shaw (2002) may not have identified any remnant till deposits overlying the gravels, which could point to a remoulding of sediments by subglacial deformation.

A potential alternative explanation for lineations containing units of sorted sediment comes from Evans (1996) who investigated a mega-fluting complex near the lower Red Deer River in Southern Alberta. This mega-fluting complex, while consisting of relatively long (up to 30km) and elongate lineations, is unusual in that the lineations are few in number and very limited in lateral extent (Evans, 1996). The sediment sequence within the lineations is generally described by Evans (1996) as consisting of two till units overlying sorted cobble gravels, which in turn overlies another till unit above a pre-glacial sequence, with all units except the upper tills displaying glaciotectonic features. Evans (1996) concludes that these features were originally formed as eskers which were remoulded during the emplacement of the two till units.

The sediments that compose the MSGLs of the Dubawnt Lake flowset are discussed briefly by Stokes *et al*. (2003) who point out that these sediments are potentially drawn from two different sources. The predominant substrate in the area is a massive granitoid gneiss which produces only thin and coarse grained tills however local outcrops of the Thelon sedimentary basin potentially provide large volumes of disaggregated and clay rich sediments (Stokes *et al*., 2003). Although these basin deposits underlie much of the trunk and terminus of the ice stream there is no close correspondence, particularly in the onset area, between ice stream margin and basin extent (Stokes *et al*., 2003). Although we have no detailed description of the composition and structures of the Dubawnt Lake lineations themselves we can perhaps infer that they are in places formed within tills with relatively high coarse fractions.

2.4. Theories of Formation

This work is primarily concerned with attempting to test the groove-ploughing formation theory, and as such much of this section will be devoted to exploring the origins and predictions of this theory. In order to provide a balanced review of MSGL formation theories, and their potential consequences for MSGL morphology, a brief examination of the other widely cited formation theories will also be necessary. A key question that will be addressed in this section is what testable (or potentially testable) predictions, particularly those related to MSGL morphology, each theory makes.

2.4.1. Bed Deformation and the Instability Theory

Observations of a deforming layer beneath modern glaciers (e.g. Boulton and Hindmarsh, 1987), and particularly ice streams (e.g. Alley *et al*., 1986), provide support for widespread sediment deformation occurring beneath ice streams. The crucial step in the development of the mechanism into a general formation theory, without the need for pre-existing obstacles at the bed, came with the proposal of Hindmarsh (1998) that the system of flowing subglacial sediment and ice at the bed was generally unstable such that the bed naturally became 'wavy'. The instability theory advanced by Hindmarsh (1998) relies on a till with a pressure dependant viscosity (driven by effective pressure change) being generally unstable when minor roughness exists at the bed. This instability mechanism in theory allows for a spontaneous generation of relief (Hindmarsh, 1998) without the need for bedrock features, or other, obstacles.

Initial suggestions that modelling of the instabilities proposed by Hindmarsh (1998) could generate drumlins proved unfounded (Clark, 2010). While the theory was capable of generating ribbed moraine (Dunlop *et al*., 2008) it was incapable of explaining the lateral instability needed to create drumlins (or MSGLs). Recent development of the theory by Fowler (2010), however, introduces a 'rilling' instability connected to feedbacks with the subglacial drainage system, which potentially allows for generation of MSGLs. Importantly, Fowler (2010) shows that the favoured wavelength of bedform growth using this model is on the scale of MSGLs and indeed calculates the preferred dimensions of MSGLs produced under this mechanism (a preferred length of 52.9 km and a preferred width of 394 m).

The expected values for MSGL length, width and spacing calculated by Fowler (2010) using the rilling instability seemingly provide a number of values that can be tested using examination of lineation morphology. It should be noted, however, that the Fowler (2010) values were calculated to demonstrate that the rilling instability theory could generate lineations with realistic dimensions and not as a specific set of values to be tested. The mathematical complexity of the current modelling approaches, and the number of unknown parameters related to deformation at the ice stream bed, make it extremely difficult at present to test this theory.

2.4.2. Meltwater Megafloods

Formation of lineations by turbulent meltwater outburst floods, proposed previously for a number of different bedforms, e.g. drumlins and rogen moraine (Shaw, 2002), provides a very different mechanism from the other theories reviewed here. The theory was used by Shaw *et al*. (2000) to explain the formation of ‘large-scale’ flutings, of MSGL dimensions, within the Athabasca fluting field, Alberta, and has recently been applied to the landsystems, including MSGLs, commonly observed within Antarctic marine troughs (Shaw *et al*., 2008).

The megaflood theory has made much use of form analogies between subglacial bedforms and other landforms (yardangs and submarine megafurrows in the case of MSGLs) formed by fluvial and aeolian processes. This form analogy approach provides evidence that landform forming instabilities exist in nature; indeed similar analogies are used by Clark (2010) in support of the deforming till instability theory. Such support for the general concept of bedform producing instability does not in itself provide support for a mega-flood theory, especially as the landforms being compared are in many cases on very different scales.

A key consideration with the megaflood theory is whether there could be sufficient storage of water, either subglacially, supraglacially or proglacially, to allow for a flood that could do sufficient geomorphic work. Clarke *et al.* (2005) note that a glacial megaflood of the sort proposed by the proponents of the megaflood theory (e.g. Shaw, 1983), would probably be much larger than that believed to have occurred during drainage of glacial Lake Agassiz. Ice sheets, furthermore, generally tend to expel subglacial water unless very significant bed gradients prevent drainage (Clarke *et al*., 2005).

Observations of ‘hook like’ morphology (see Figure 2.5), from Munro-Stasiuk and Shaw (2002), and appearances of crescentic overdeepenings from other studies (e.g. Ó Cofaigh *et al*., 2005) are cited as evidence in support of the megaflood theory. The fact that these observations are certainly not ubiquitous across any palaeo-ice stream bed studied in the literature weakens this argument. The most compelling evidence contradicting the megaflood theory, however, comes from the radar and seismic observations of the bed of the Rutford Ice Stream (King *et al*., 2009). The gradual formation of MSGLs without any significant change in ice surface elevation being observed over the study period, which would have indicated major changes in subglacial drainage, clearly is not compatible with the megaflood theory (Ó Cofaigh *et al*., 2010).

2.4.3. Groove-Ploughing

The concept of the ploughing of sediment by ice keels extending from the ice base into a deformable sediment substrate, and potentially eroding underlying stiffer sediment, was first proposed by Tulaczyk *et al*. (2001). This idea potentially allows for deformation of sediment at depth even within a till with coloumb-plastic rheology, i.e. one that deforms by plastic failure in very thin upper zones. Tulaczyk *et al*. (2001) regarded ice stream bedforms, particularly MSGLs, as potential evidence for ploughing by ice keels and the theoretical plausibility of this mechanism of MSGL formation is supported by Clark *et al*. (2003) who successfully modelled the possibility of ice keel survival over the length scale of MSGLs.

Groove-ploughing relies on the ice base being shaped by bedrock roughness elements, or bumps, located slightly upstream of the bedrock to sediment transition before acting as rigid keels which plough the sediment layer (Clark *et al*., 2003). The morphology of the resulting bedforms is thus controlled by the spacing and amplitude of initial bedrock roughness, flow patterns within the ice stream and the downstream survival of the ice keel. It was also suggested by Clark *et al*., 2003 that subvertical shear planes within the basal ice, caused by convergent ice stream flow patterns, could create the keels required for groove-ploughing without the need for bedrock obstacles.

Downstream survival of ice keels was modelled by Clark *et al*. (2003) using a lithostatic stress value determined by the density contrast at the ice-bed interface. This model failed to produce grooves on the MSGL scale regardless of the bedrock roughness parameters used. Using an additional assumption of flow striping, bedrock bumps forming downstream ridges and troughs on the ice surface, in order to slightly reduce lithostatic stress at the bed, however, allowed the Clark *et al*. (2003) model to produce MSGL-like grooves.

Groove-ploughing suggests a predominantly erosional origin for MSGLs, unlike subglacial sediment deformation, with some squeezing of till to form intervening ridges. As such it is suggested by Clark *et al*. (2003) that MSGL morphology will depend partially on the rheology of the till. In a drier and stronger till it is suggested that ploughing may produce grooves with no intervening ridges since this till would not be as readily squeezed and mobilised laterally (Clark *et al*., 2003). It is possible to conceive that such a process may account for megagrooves, however, these features have only been observed in bedrock settings and groove-ploughing is therefore unlikely as a formational process for these landforms (Bradwell, 2005).

The initial proposal of the groove-ploughing theory by Clark *et al*. (2003) was accompanied by ten predictions regarding MSGL morphology, sedimentology and relation to bedrock bumps. Predictions 1 to 3 deal with the relationship between basal roughness and ice keels. Prediction 4 suggests that MSGL morphology should be related to the amount of convergence of the ice stream. Prediction 5 deals with the expected downstream change in lineation amplitude and groove width. Predictions 6-8 deal with the relationship between the sediment present and the form of the MSGL produced. Finally predictions 9 and 10 suggest that ice keels might cross the grounding line and plough different features beneath the ice shelf.

Some limited testing of the predictions of the groove-ploughing theory has previously been carried out (e.g. Ó Cofaigh *et al*., 2005; Graham *et al*., 2009). There has, however, been no comprehensive investigation of the detail of MSGL morphology, which would be required to test the groove-ploughing predictions. Other observations such as the grooving of internal reflectors within the sediment sequence of Antarctic troughs and bifurcation of MSGLs (Ó

Cofaigh *et al*., 2005) may also have a bearing on the plausibility of groove-ploughing as a formation theory.

The prediction that MSGL groove depth and width would decrease downflow (prediction 5 in Clark *et al*., 2003) was investigated by Clark *et al*. (2003) using data from the lineations (bundle structures) in the Gerlache-Boyd trough. Although this test found this to be generally true for the individual lineations investigated, the morphological differences between the bundle structures studied and the wider MSGL population noted above, raises questions as to the applicability of this investigation as a general test of groove-ploughing. Results from lineations in Marguerite trough (Ó Cofaigh *et al*., 2005) also show a downflow decrease in mean wavelength, however, mean amplitude is found to remain approximately constant downstream with some individual ridges displaying amplitude increase. Comprehensive testing of this prediction in multiple palaeo-ice streams and with larger samples of lineations is required to resolve these disparate observations.

The groove-ploughing theory suggests a direct relationship between MSGLs and upstream bedrock bumps which generally should have an expression on the palaeo-ice stream bed (Clark *et al*., 2003). A few observations of individual lineations emanating from bedrock bumps in northern Norway (Ottesen *et al*., 2008) support the link between MSGLs and basal roughness. However, observations from Marguerite trough (Ó Cofaigh *et al*., 2005) and beneath the current Rutford ice stream (King *et al*., 2009) show no clear relationship between bedrock bumps and MSGLs. A further suggestion proposed by Clark *et al*. (2003) of basal roughness production by englacial subvertical shear planes, that are a result of convergence within the ice stream onset zone, does not require bedrock roughness; this hypothesis is not, however, explored in detail by Clark *et al*. (2003).

The interpretation of lineation bifurcation from the Marguerite trough, as already mentioned in this section, is potentially hard to reconcile with a single episode of groove-ploughing (Ó Cofaigh *et al*., 2005). It is, however, unclear how widespread MSGL bifurcation is and hence it remains possible that a small number of such observations can be attributed to a limited secondary phase of groove-ploughing. Active formation of MSGLs directly downstream of the grooves of other lineations as observed by repeated seismic surveying of the Rutford Ice Stream (King *et al*., 2009) presents a potentially more serious problem for the groove-ploughing theory. Although the King *et al*. (2009) observations are over a relatively short time period the evidence presented for erosion and deposition of lineations over large areas of the bed, on decadal timescales, does not seem to be compatible with ploughing by ice keels.

2.5. Discussion

The vast majority of MSGL flowsets discussed in the literature are described as comprising ridges of high parallel conformity with little deviation in form from those originally described by Clark (1993). Bedrock megagrooves (e.g. Bradwell, 2005) and the bundle structures within the Gerlache-Boyd trough (Canals, 2000), however, provide exceptions and it remains to be seen if these features are genetically related to the ‘main’ MSGL population. The proposal that MSGLs are part of a morphological bedform continuum (Rose, 1987) also remains to be tested by examination of large samples of MSGL morphology data. Whether MSGLs are actually a single population of landforms and what is the nature of their relationship with less elongate bedforms, thus remain open questions. Detailed observations of MSGL morphology and downflow change (e.g. Clark *et al.*, 2003; Ó Cofaigh *et al*., 2005), however, has proved of some use as a test of specific predictions made by formation theories.

At present it is not clear if any single formation theory, which has been fully explored in the literature, is able to explain all of the morphological observations. The groove-ploughing theory has been challenged by observations of bifurcation, as well as a lack of downstream decrease in lineation amplitude in Marguerite trough (Ó Cofaigh *et al*., 2005). The parabolic depressions and ‘hook like’ morphology put forward in support of the megaflood theory (Munro-Stasiuk and Shaw, 2002) do not appear to be widespread observations. In contrast, the deforming instability theory has not yet advanced predictions of MSGL morphology with the possible exception of ‘preferred’ length and width values (see Fowler, 2010) which remain to be fully tested.

2.5.1. What observations does a MSGL formation theory need to explain?

The list below is an attempt to define the characteristics required of a successful MSGL formation theory. These characteristics have been split into two categories either because of the potential for features displaying similar morphology to MSGLs to be genetically separate from the main MSGL population or the relatively small numbers of observations of given characteristics.

- Formation in fields with long axes sub-parallel to ice flow.
- Formation within topographically and non-topographically controlled ice streams.
- Formation within marine and terrestrially terminating ice streams.
- Relatively uniform 'ridge-and-groove' morphology (potentially with some outliers).
- Lineation dimensions (Tables 2.1, 2.2 and 2.3) of 1-80 km (length), 100-500 m (width), 2-15 m (amplitude) and 100-1000 m (lateral spacing).

Observations that may also possibly be included:

- Formation downstream of less elongate bedforms.
- Formation on crystalline (Dubawnt Lake) as well as sedimentary substrates.
- Relatively short period of formation (Rutford ice stream observations – King *et al.*, 2009).
- Formation in deformation tills and pre-existing (fluvial) sediments (Munro-Stasiuk and Shaw, 2002).
- Formation in isolated complexes (Evans, 1996).
- Bifurcation of MSGL ridges (Ó Cofaigh *et al*., 2005).

- Lineation dimensions (Tables 2.1, 2.2 and 2.3) of up to 180 km (length), 5000 m (width), 50 m (amplitude) and 5000 m (lateral spacing).

2.6. Conclusion

Despite a number of recent publications that have investigated palaeo-ice stream flow sets, the present understanding of MSGL morphology is limited by a lack of large datasets (in contrast to drumlins (Clark *et al*., 2009)). The majority of descriptions of MSGL morphology are simply unsystematic presentations of a number of typical values, e.g. length, width and elongation ratio, for a given flow set. A number of limited morphological observations, e.g. downstream ridge spacing decrease in the Gerlache-Boyd trough (Clark *et al*., 2003) have, however, been used to provide support for proposed formation theories. The continuing development of formation theories, e.g. the preferred dimensions of MSGLs produced by Fowler (2010), will probably allow for further morphological predictions which will require testing against extensive sets of observations.

All the formation theories discussed here have significant problems either in their ability to generate bedforms, or from morphological and compositional observations. It is also notable that only the groove-ploughing theory has a range of predictions, relating to lineation morphology, which can be tested by examining the morphology of lineations from palaeo-ice stream beds. In particular, the predictions regarding downstream change in lineation spacing and amplitude are the primary focus of the methods devised to test the groove-ploughing theory.

3. Methods

3.1. Introduction

Investigating the morphology of MSGLs and testing the groove-ploughing theory requires the development of several new measurement techniques. Given the lack of systematic study of the morphometry of MSGL populations in the literature (see Section 2.2.1) it will also be necessary to consider how quantities like lineation width should be defined and measured. Examining the testable predictions of groove-ploughing (as identified in Section 2.4.3) will, furthermore, require some techniques that have not previously been used to study MSGL morphometry. Attempting to gauge how rigorous these measures are as tests of the groove-ploughing theory will clearly be a key consideration in this project.

To examine lineation morphology some form of digitisation, using GIS software, is necessary in order to determine lineation position and shape. This process of digitisation necessarily introduces the judgement of the user as well as the resolution, and nature, of the imagery used into the analytical process. The first part of this chapter will explain both the digitisation process and the methods used to extract length, width and elongation ratio.

The morphological predictions of the groove-ploughing theory identified as providing potential tests of this theory are those relating to downstream change in lateral lineation spacing and lineation amplitude. Given the irregular shape of some of the lineations digitised and the necessity (for measuring lineation amplitude) of compensating for trough topography it is difficult to devise universally applicable and rigorous tests of these predictions. In some cases it has been necessary to make assumptions (or approximations) regarding factors like the relative position of the centreline of the lineations in order to create tests which can feasibly be applied to the MSGL populations investigated. The second part of this chapter will explain the different methods, devised to test the two predictions of the groove-ploughing theory and explore the assumptions on which these methods rely.

3.2. Introduction to the palaeo-ice stream beds studied

The primary criteria for choosing the palaeo-ice streams were the apparent preservation of the lineations and the availability of suitable imagery. It was also considered that choosing sites from different palaeo-ice sheets, and in different topographical settings, would ensure that any conclusions drawn were not likely to be specific to a particular setting or flow regime. Two of the palaeo-ice streams chosen (Marguerite Trough and Malangsdjupet) are situated in marine troughs, whereas the third (Dubawnt Lake) is not topographically constrained. It is notable that the imagery available for Marguerite Bay and Malangsdjupet allows for examination of lineation amplitude, whereas the imagery available for Dubawnt Lake does not have elevation data.

3.2.1. Dubawnt Lake

The Dubawnt Lake palaeo-ice stream is located on the north-western edge of the Canadian Shield within the Nunavut and Northwestern Territories. Various authors (e.g. Prest *et al*., 1967; Boulton and Clark, 1990) have mapped the Dubawnt Lake flow set as a flow pattern within broader scale mapping. The first detailed mapping of a large portion of the lineation population, as polylines, was carried out by Stokes and Clark (2002). This digitising of 8,856 lineations from the Dubawnt Lake flowset, by Stokes and Clark (2002), found a mean length of 4000 m for lineations in the trunk of the flowset.

The palaeo-ice stream bed takes the form of a wide upstream convergence zone narrowing to a central ‘trunk’ zone (see Figure 4.1) before spreading out to a lobate terminus (Stokes and Clark, 2003). Stokes and Clark (2002) found that the longest and most elongate bedforms are found in the central trunk zone of the flowset. It is clear, however, that areas of long and elongate lineations are not solely confined to the trunk zone and that some relatively ‘stubby’ lineations are also found in the trunk (Stokes and Clark, 2002).

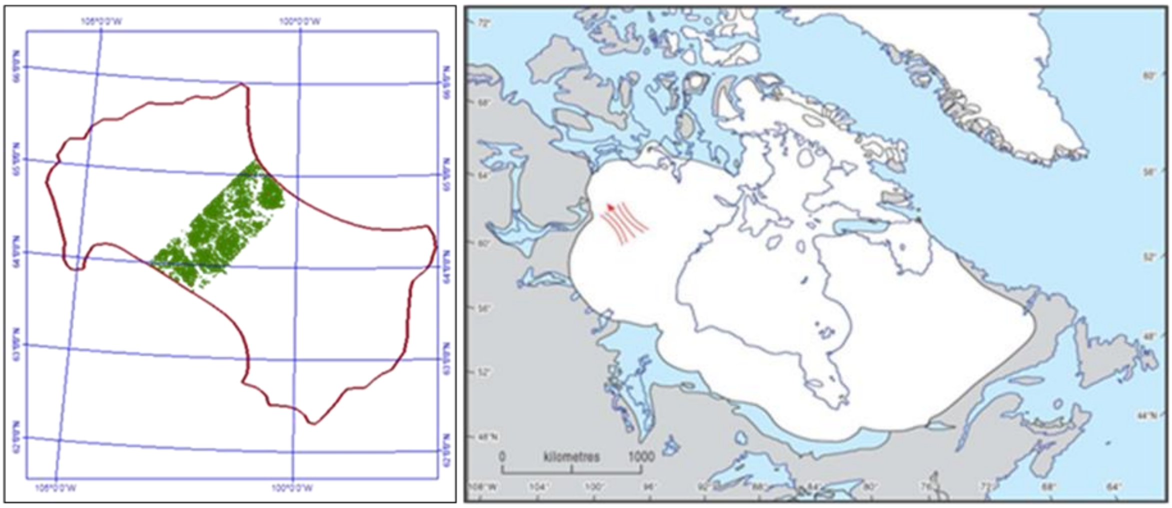

Figure 3.1: *Location of the Dubawnt Lake palaeo-ice stream bed. The upper pane shows the location of the flowset within the conjectured limits of the former Laurentide Ice Sheet. The lower pane shows the lineations mapped, as polygons, in this project compared to the full extent of the flowset. The image in the top image is taken from Stokes et al., in prep.*

The formation of the Dubawnt lake flowset has previously been attributed to the action of a surge event possibly in relation to proglacial lake drainage (Kleman and Borgström, 1996). The palaeo-ice stream interpretation was suggested by Stokes and Clark, (2003) on the basis of the flow set's similarities to the theoretical model of the glacial land system of an ice stream proposed by Stokes and Clark (1999). In particular, the convergent pattern of the flowset and the abrupt lateral margins are suggested to be indicative of a palaeo-ice stream bed (Stokes and Clark, 2003).

Unlike the other palaeo-ice streams investigated in this work, the Dubawnt Lake palaeo-ice stream was not topographically controlled (Stokes and Clark, 2003) although the area has only relatively gentle slopes. The area occupied by the Dubawnt Lake flowset is primarily underlain by Precambrian bedrock which is likely to have yielded relatively little debris under glacial erosion and produced primarily coarse grained tills (Stokes and Clark, 2003). There are in places, however, outcrops of sedimentary rocks which may have provided significant volumes of fine grained, clayey, sediment (Stokes and Clark, 2003).

3.2.2. Marguerite Bay

Marguerite Bay is located on the west side of the Antarctic Peninsula (Figure 4.6) with water depths in the bay ranging from 500 to 1600 m (Dowdeswell et al., 2004). A swath bathymetry study of the area reported by Ó Cofaigh *et al.* (2002), showed a trough extending from the inner shelf (with water depths of up to 1600 m) to the edge of the shelf (with water depths decreasing to around 500 m). Within this trough Ó Cofaigh *et al.* (2002) note a number of different bedforms including, towards the shelf edge, highly elongate MSGLs formed within an acoustically transparent sediment layer.

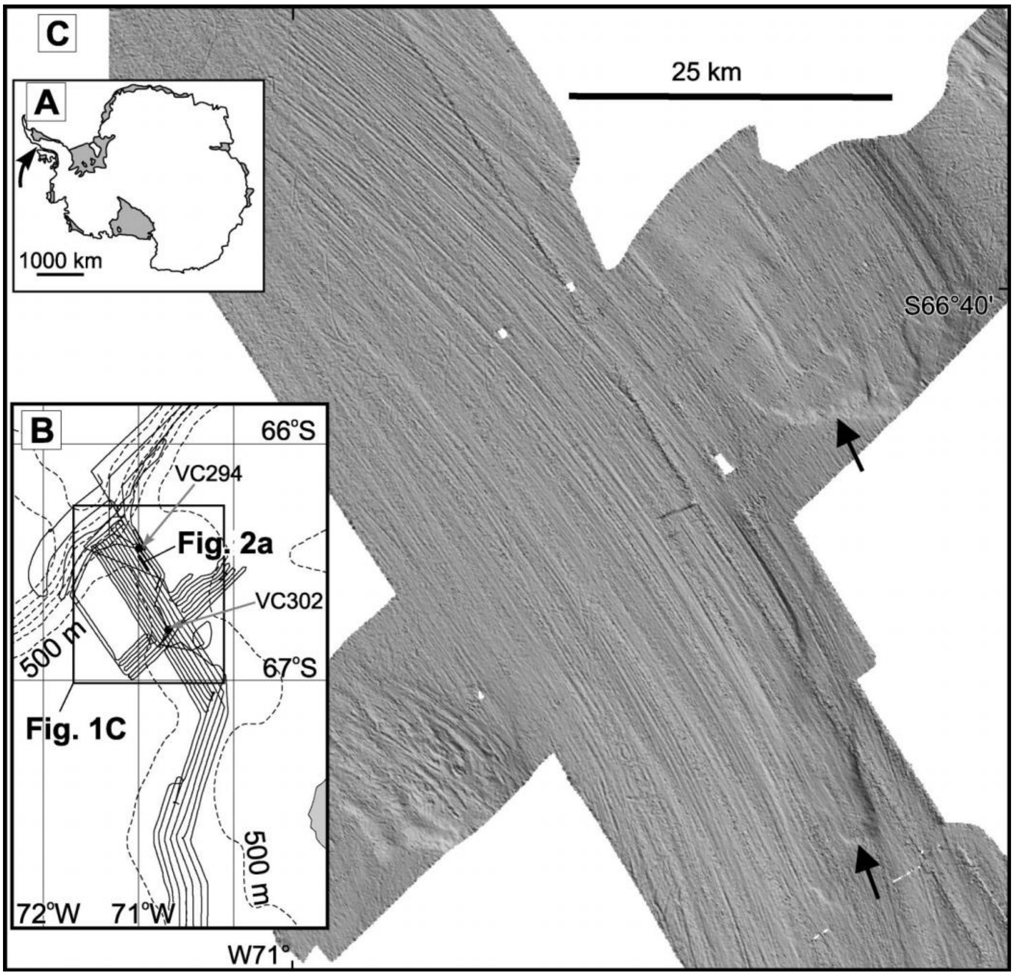

Figure 3.2: *Location of the Marguerite Bay palaeo-ice stream bed. Pane A shows the location relative to the Antarctic Peninsula and the rest of Antarctica while Pane B shows the tracks of the RSS James Clark Ross along the length of Marguerite Trough. The main image (Pane C) shows a shaded relief image compiled from the bathymetric data collected by the echo sounders aboard the RSS James Clark Ross. The image shows a large number of lineations and two prominent grounding zone wedges are indicated by the two arrows. Images taken from Dowdeswell et al. (2004).*

The nature of the trough and the bedform flowsets it contains were suggested by Ó Cofaigh *et al*. (2002) to be indicative of the presence of a grounded ice stream flowing west through the trough during the last glaciation when the Antarctic Peninsula Sheet expanded across the continental shelf. This conclusion was based on bedform orientation, which indicated convergent flow, increasing bedform elongation down-trough and the geometry of the trough itself (Ó Cofaigh *et al*., 2002).

Investigation of the sediments within the trough, using both seismic techniques and coring, showed two diamicts overlain by relatively fine glacimarine units (Ó Cofaigh *et al*., 2005). The upper 'soft' diamict in which the MSGLs are formed has been investigated by both acoustic methods and coring (e.g. Dowdeswell *et al*., 2004 and Ó Cofaigh *et al*., 2005). This diamict has been found to be matrix-supported and massive, with a relatively low shear strength and composed of a silty/clayey mud. Ó Cofaigh *et al*. (2007) suggests the 'soft' diamict to be a hybrid subglacial till, formed by a combination of lodgement and deformation.

3.2.3. Malangsdjupet

Malangsdjupet is one of several cross shelf troughs, separated by shallow banks, along the north Norwegian continental shelf entering into the Barents Sea (Figure 3.3) (Ottesen *et al.*, 2008). Within Malangsdjupet, and neighbouring troughs, Ottesen *et al*. (2005) report MSGLs as well as grounding zone wedges and lateral shear margin moraines. Ottesen *et al.* (2008) report typical values of MSGL width as 350 m, with ridge height of 8-16 m and crest-to-crest spacing of up to 450 m. A number of the lineations observed by Ottesen *et al.* (2008) are noted to emanate directly from bedrock obstacles, an observation that could potentially support a groove-ploughing origin.

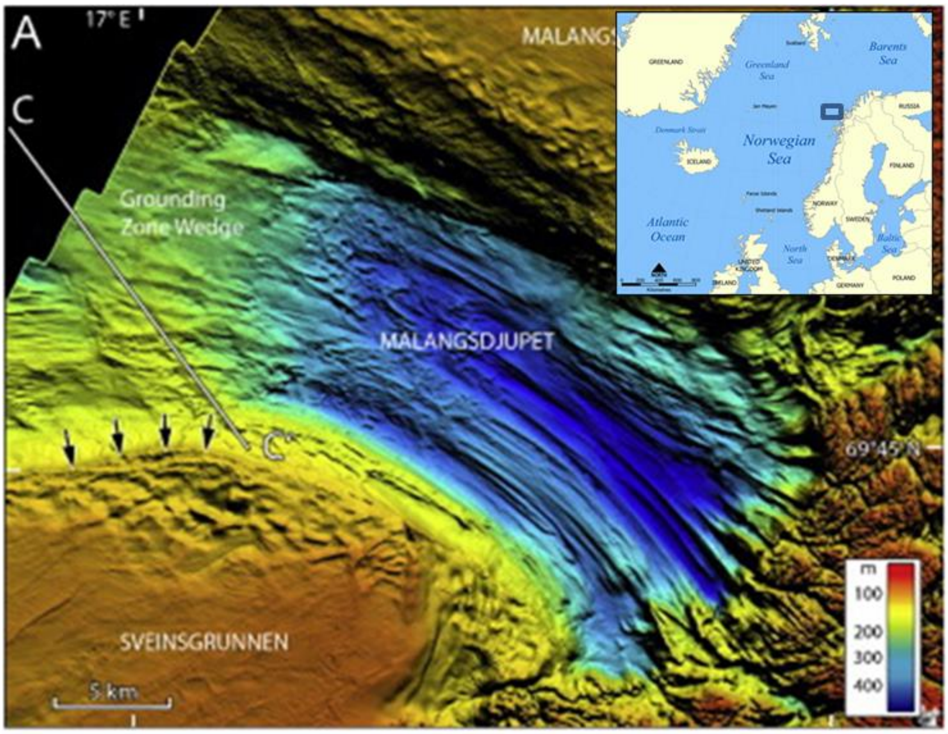

Figure 3.3: *Shaded relief image of the Malangsdjupet palaeo-ice stream bed (located within a cross shelf trough), with inset map showing the palaeo-ice stream's position relative to the Norwegian coast. From Ottesen et al., 2008.*

On the basis of the flowsets of lineations they contain and their association with trough mouth fans, Ottesen *et al*. (2005) interpret the Norwegian cross shelf troughs, as evidence of palaeo-ice streams draining the former Scandinavian Ice Sheet(s) potentially over multiple glaciations. Ottesen *et al*. (2008) interpret the fjord features as onset, or tributary, zones with ice streaming reaching maximum velocity within the larger cross-shelf torughs. The shallow banks between the troughs have some moraine systems and some evidence for iceberg scouring (Ottesen *et al*., 2008)

3.3. Lineation Mapping

In order to test the morphological predictions made by the groove-ploughing theory, as stated in Clark *et al*. (2003), it is necessary to map a large number of lineations from the various different palaeo-ice stream beds. Lineation mapping is a necessary first step in order to identify the location and extent of the lineations, which then allows for measures of lineation spacing and height to be derived. This section will review the process of mapping lineations and attempt to highlight the assumptions inherent in this process and the possible sources of error that might affect later analysis.

3.3.1. Imagery:

To allow examination of lineation elevation it is, ideally, necessary to have imagery of the palaeo-ice stream bed from which both lineation position and height can be determined. The spatial resolution of the imagery determines what scale of feature can be digitised and with what level of accuracy. For DEMs the magnitude of the vertical uncertainty potentially plays a key role in determining how thoroughly predictions of lineation amplitude can be tested, particularly given the relatively low amplitude of most of the lineations being studied.

3.3.1.1. Dubawnt Lake

Coverage of the Dubawnt Lake palaeo-ice stream bed was available from a series of orthorectified images from the Landsat Enhanced Thematic Mapper Plus satellite. This multispectral imagery has 8 bands with a spatial resolution of 30 m for bands 1-5 and 7 (band 6 = 60 m) while band 8 (panchromatic) has 15 m resolution. Various different band combinations were used during lineation digitisation in order to compensate for the effects of any changes in land surface cover. This imagery has previously been used for the mapping of MSGLs by Stokes *et al*. (2003) and Spagnolo *et al*. (2010) in which it was shown to be of sufficient resolution to allow for digitising of lineations as both lines and polygons.

This imagery does not allow for determination of lineation height and no DEM of suitable vertical resolution exists for this area of Canada. It is thus only the prediction relating to the lateral spacing of lineations that can be tested for the Dubawnt Lake flowset. The large number of well-preserved lineations (in a single flowset) in this area, however, makes this palaeo-ice stream bed an ideal site to analyse the lateral spacing of lineations.

3.3.1.2. Marguerite Bay

Digitisation of the lineations within Marguerite Trough used swath bathymetric data collected on cruises of the RRS James Clark Ross in 2002 and 2003 (Ó Cofaigh *et al.*, 2005) and previously used by Dowdeswell *et al*. (2004) and Ó Cofaigh *et al*. (2005). This imagery was gridded (25-50 m cell size) and processed to remove anomalous data points (as described by Ó Cofaigh *et al*. (2005)). Vertical uncertainty of this bathymetric imagery is approximately 1 m and across track horizontal uncertainty is approximately 5 m (Dowdeswell *et al*., 2004). While the horizontal resolution of the imagery seems entirely adequate to the mapping of the lineations, the limited vertical resolution, lineation amplitude is estimated at 2-8 m by Ó Cofaigh *et al*. (2005), may hamper the analysis of change in lineation elevation.

3.3.1.3. Norwegian Cross Shelf Troughs:

Imagery of the Norwegian palaeo-ice stream beds of Malangsdjupet and Andfjorden was taken from swath bathymetry studies of the continental shelf carried out by the Norwegian Hydrographic Service. The data were gridded with a horizontal cell size of 50 m and the vertical accuracy of this data is between 0.5 and 1% of water depth (Ottesen *et al*., 2008). As most of the features mapped in the two studied troughs are between water depths of 200 m and 500 m this equates to vertical accuracy of 1-5 m. Shaded relief images of the troughs were used during digitisation of lineations.

3.3.2. Digitising Lineations:

All lineations mapped in this project were digitised on-screen as polygons using ArcMap (Figure 3.1). Where possible several different shaded relief images, illuminated from a number of different angles, of the lineations were used (for the bathymetric imagery from Marguerite Trough and Malangsdjupet) in order to limit mapping bias that could be due to angle of DEM illumination. Several different combinations of spectral bands were used for the Dubawnt Lake mapping, in order to limit the influence of differing vegetation cover on lineation digitisation. When working with the DEM imagery the ArcMap slope tool, which produces an output raster displaying local slope gradient, was also used as another aid to highlighting the edges of the lineatons.

The reason for digitising as polygons, rather than as lines, was that properly testing the groove-ploughing prediction relating to the lateral spacing of lineations requires measurement of the lateral distance between lineation ‘edges’. Digitising of polygons was carried out around lineation break-of-slope with particular attention being paid to accurately representing the upstream and downstream ends of the lineations, as these are more difficult to accurately digitise than the (much longer) lineation edges aligned parallel to the palaeo-ice flow direction.

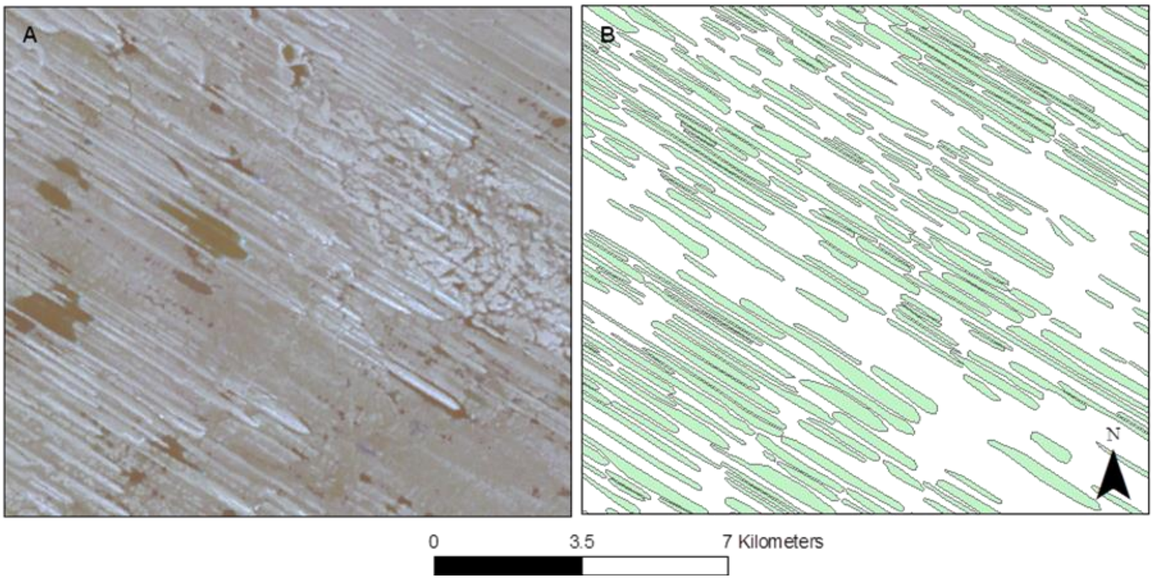

Figure 3.4: *Example of lineation digitisation using the Dubawnt Lake imagery. ‘A’ is a Landsat image while ‘B’ shows the same area of the palaeo-ice stream bed with lineations represented as polygons.*

The manual approach to the digitisation of lineations means that both the mappers’ conception of MSGL morphology and human error is introduced into the mapping process. This is both impossible to avoid, while using a manual approach, and very difficult to quantify. That the same mapper has been used for each of the three palaeo-ice stream beds should mean that there should be a degree of consistency between the results for the each of the three palaeo-ice streams. Image resolution and the fact that there are two different types of imagery used in this study, DEMs and spectral imagery, is another possible source of error. This type of error is similarly hard to quantify, but it can be noted that the ability to illuminate the DEM imagery from different directions is likely to mean that the results from this mapping is more robust.

While mapping lineations, no particular definition, or limit, was applied to determine which lineations could be classed as MSGLs rather than drumlins or any other class of lineation. The reasoning behind this was that lineations of differing lengths and elongation ratios appear side by side on the three palaeo-ice stream beds, while various authors (e.g. Rose, 1987) have suggested bedform classifications like drumlins, mega-drumlins and MSGLs exist as part of a morphological continuum and are thus not clearly distinct from one another (see Section 1.2). Despite this lack of a precise definition of MSGLs as a landform class it was, however, deemed necessary to focus on digitising areas of the palaeo-ice stream bed where lineations were generally most elongate.

For the marine troughs the mapped area composed primarily of highly elongate lineations tended to be the outer trough zone, while for the Dubawnt Lake palaeo-ice stream the mapped area was located in the central trunk zone (Figure 3.1) as identified by Stokes *et al*. (2003). A particular problem was whether to digitise all of the lineations or to choose just the areas containing the most elongate lineations. After examining the palaeo-ice stream bed it was decided that only the most elongate lineations on the outer shelf would be digitised, as the majority of the lineations in the upstream areas seem to have relatively low elongation ratios.

In contrast to the manual approach to lineation digitisation, chosen for this work, a number of recent studies (e.g. Smith *et al*., 2009; Saha *et al.*, 2011; Hillier and Smith, 2012) have used automated, or semi-automated, methods to extract morphological parameters (such as lineation length, width and elevation). The ‘cookie cutter’ method described by Smith *et al.* (2009) uses manual digitisation to guide automated extraction of a lineation from a DEM. A fully automated method for lineation digitisation is used by Saha *et al.* (2011), and involves using a number of user defined rules to process elevation and slope angle data. Such automated methods, however, require relatively high resolution DEMs, and as the only imagery available for the Dubawnt Lake site is Landsat ETM imagery manual digitisation is the most appropriate option.

3.4. Lineation Morphology

The lack of systematic reporting of lineation morphology in the literature (as discussed in Section 2.2.1) has resulted in continuing uncertainty regarding the morphological relation of MSGL populations to one another and the relation of MSGLs to other landform classifications (e.g. drumlins and mega-drumlins). The digitising of large numbers of lineations, from several palaeo-ice stream beds, necessary to test the groove-ploughing theory also presents an opportunity to examine these questions. Determining the range of length, width and elongation ratio values, as well as the distributions of these measures, is also potentially helpful as a general test of MSGL formation theories.

3.4.1. Morphology of lineation populations

Lineation length was determined using lines connecting the lineation end points, determined as the feature vertices with minimum and maximum X coordinate, and the lineation centroid. The overall lineation length is calculated as the sum of the lengths of these two lines. The advantage of this technique is that in using three points it allows for measurement of lineations with some degree of irregularity in shape. This method was found, however, to poorly fit very long lineations in the area of the Marguerite Bay palaeo-ice stream where the trough changes direction and some lineations display considerable curvature. It was therefore found necessary to exclude lineations from this part of the Marguerite Bay palaeo-ice stream bed in morphometry calculations and all subsequent analysis.

The concept of lineation width is one that requires more careful consideration given the potential for variation along the considerable length of the lineations. One possible method of measuring is that used, for drumlins, by Spagnolo *et al.* (2010) which finds the longest line, within the digitised polygon, perpendicular to the longest (longitudinal) line within the polygon. Given the great length and very high elongation ratios of many of the lineations studied a measure of average lineation width is considered preferable for this project. The method chosen approximates lineations to a rectangle by dividing lineation area by lineation length. Although this method clearly relies on a simplification of lineation shape it seems to be largely valid given the observed shape of many of the lineations in this study. Lineation elongation ratio will simply be calculated by dividing the width values by the length values for each lineation.

3.4.2. Lineation merging and bifurcation

It has been suggested by Ó Cofaigh *et al.* (2005) that lineations within Marguerite Trough show evidence of merging or bifurcating downstream. This observation is one that it does not seem possible to reconcile with the groove-ploughing theory unless what is interpreted as merging/bifurcation is in fact an example of subtle cross cutting of lineations. Detailed examination of these apparent occurrences of merging or bifurcation within Marguerite Trough, and any similar features elsewhere, could provide an interesting qualitative test of the groove-ploughing theory.

Examination of lineation bifurcation is likely to be largely qualitative and will mainly take the form of reproduction of imagery showing potential examples of lineation merging or bifurcation. It may also be possible to use extraction of elevation values along the lineation crests around the possible point of lineation bifurcation or merging. Although this is likely to provide only fragmentary evidence the importance of this observation in the context of the groove-ploughing theory means that only a small number of 'confirmed' observations of lineation bifurcation may serve to cast doubt on the widespread applicability of the groove-ploughing theory.

3.5. Lateral Spacing of Lineations

Change in lateral spacing of lineations is the morphological characteristic which can be examined for all of the palaeo-ice stream beds investigated in this study. The groove-ploughing theory predicts that groove width should increase (or remain constant), and conversely that lineation width should decrease (or remain constant), in the downstream direction due to melt-out of the ice keel ploughing the groove (Figure 3.5). It is possible to measure distance between lineations for all of the palaeo-ice stream beds mapped, however the exact method of measuring this parameter and the methodology used to examine downstream change in these values must first be chosen.

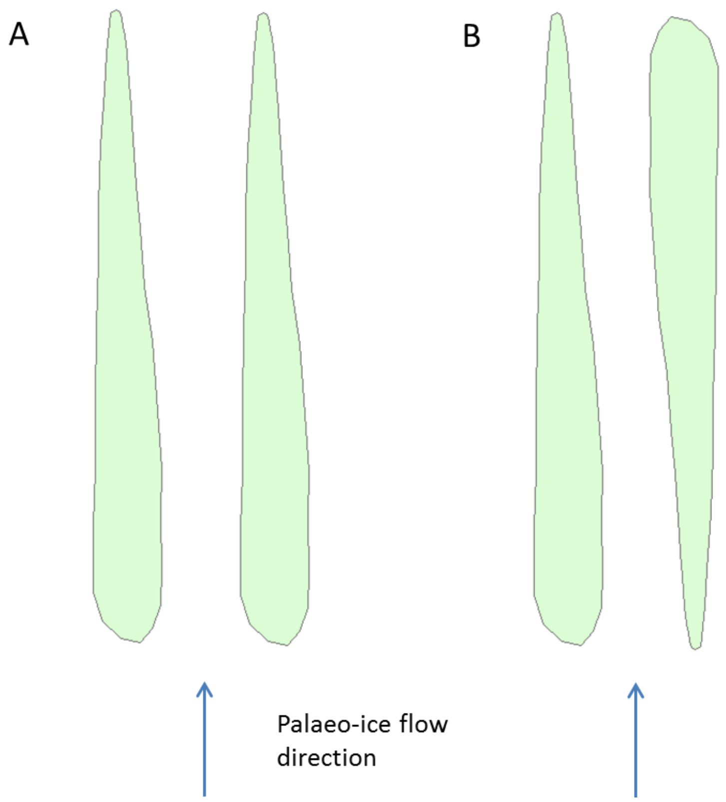

Figure 3.5: *Conceptual diagram showing the downstream variation in lineation lateral spacing expected if: A The predictions of the groove-ploughing theory (see Section 2.4.3) are fulfilled, or B. The predicted downstream increase in lateral spacing is not observed.*

3.5.1. Relative Position of Lineation Centroid

A measure of the change in the lateral spacing of lineations can be derived from the relative location of the lineation centroid. The centroid of a shape is defined as the weighted mean of all points within the shape. As such the centroid of a lineation with more of its area concentrated at the upstream end of the polygon would be accordingly positioned nearer the lineations upstream end, as shown by Figure 3.6. A lineation that conforms to the groove-ploughing prediction is expected to have a shorter distance between its downstream endpoint and its centroid (Figure 3.6), whereas a lineation that doesn't conform to this prediction would have a longer distance between its upstream endpoint and its centroid.

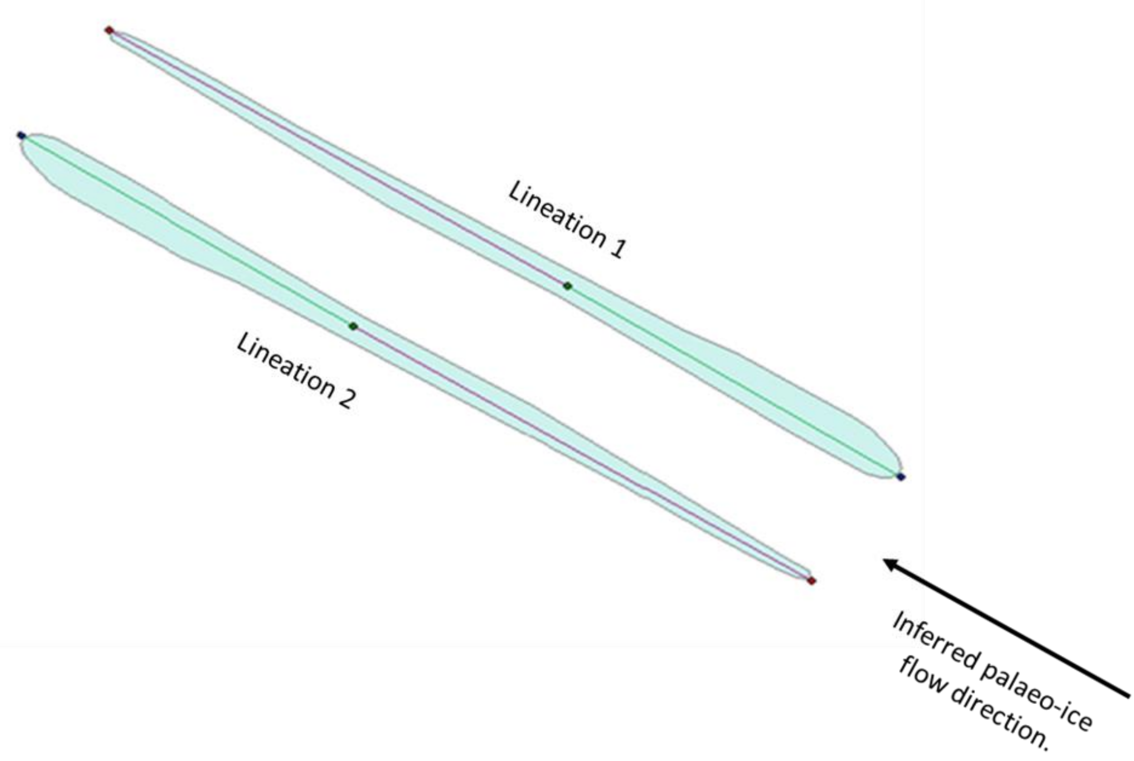

Figure 3.6: *Digitised lineations with centre of gravity point and lineation end points marked. The ratio between the length of the line between the centroid and the downstream lineation end point and the sum of the length of the two lines is the measure used to test lineation asymmetry. Note that Lineation 1 displays the asymmetry predicted by groove-ploughing whereas Lineation 2 displays asymmetry in the opposite sense.*

The centroid of each polygon was calculated using a tool in the GIS software 'ArcMap'. In order to determine the relative position of the centroid point with respect to the lineation length, lines were drawn between the centroid point and the lineation endpoints. Calculating the difference between the lengths of these two lines and expressing the difference as a percentage of the lineation length produces a simple measure of lineation asymmetry. A value of 0.5 would, therefore, mean that the lineation centroid was located half way between the lineation endpoints and suggest that the lineation was symmetrical.

This technique is similar to the asymmetry measure used, for drumlin populations, by Spagnolo *et al*. (2010). It differs, however, in using the lineation centroid rather than the longest line perpendicular to the longest straight line within the polygon. It is probably preferable to use the location of a point determined by the distribution of area, like the lineation centroid, as the MSGLs studied generally display relatively little variation in width along their length. As such it is possible that a method relying on greatest polygon width may be less reliable (or at least more likely to be significantly affected by errors made during lineation digitisation) for very elongate features (like MSGLs) than for less elongate features (like drumlins).

3.6. Lineation Amplitude

The second prediction of the groove-ploughing theory that was identified as providing a test based on the morphology of the lineations was that amplitude of any given lineation should decrease in the downstream direction. To be able to test this prediction it is necessary to find ways of extracting lineation amplitude either along the entire length of the lineation ridge crest or at points along the lineation length. This requires a method of separating the elevation change due solely to the MSGL, from the elevation change due to the topography of the trough in which they are located or due to other landforms such as grounding zone wedges.

3.6.1. Transects

A measure that was adopted by Ó Cofaigh *et al.* (2005) in order to examine change in lineation elevation was the use of transects arranged perpendicularly to the approximate average direction of the major axis of the lineations. Four transects spread along the entire length of Marguerite trough were used by Ó Cofaigh *et al.* (2005) to measure lineation amplitude. A similar technique with a number of groups of transects,Figure 3.7, will allow for testing of the groove-ploughing prediction that individual lineations decrease in amplitude downstream.

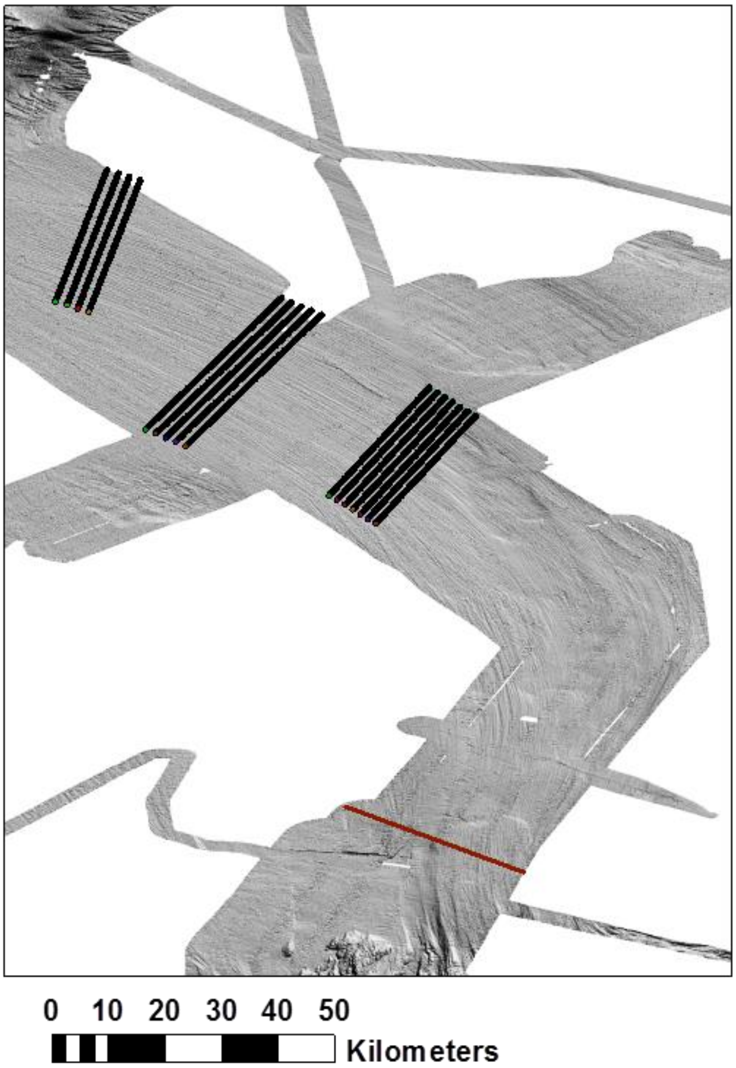

Figure 3.7: *Hillshade image of the outer area of the Marguerite Bay palaeo-ice stream derived from swath bathymetry. The red line represents the upstream limit of lineation mapping chosen in this study, while the remaining lines (and points) are the locations of the profiles extracted to examine downstream change in lineation elevation.*

The transects, shown in Figure 3.7, were placed 1 km apart from one another in groups along the length of the palaeo-ice stream bed and were aligned roughly perpendicular to the local direction of lineation major axes. The transects were drawn as polylines, onto which points were placed at intervals of 0.0005 degrees (the width of the image pixels) in order to extract elevation values. Prior to further analysis of elevation it is necessary to manually extract the points along the transect which coincide with the areas around those lineations which cut a given number of transects within the group of transects (this process is illustrated in Figure 3.8). This step is necessary in order ensure that each profile measures the elevation of the same lineations and can thus determine what downstream change in elevation takes place. For example the pixels around the green lineations in Figure 3.8 would form the first group extracted from each of the profiles in order produce the type of data seen in Figure 3.9.

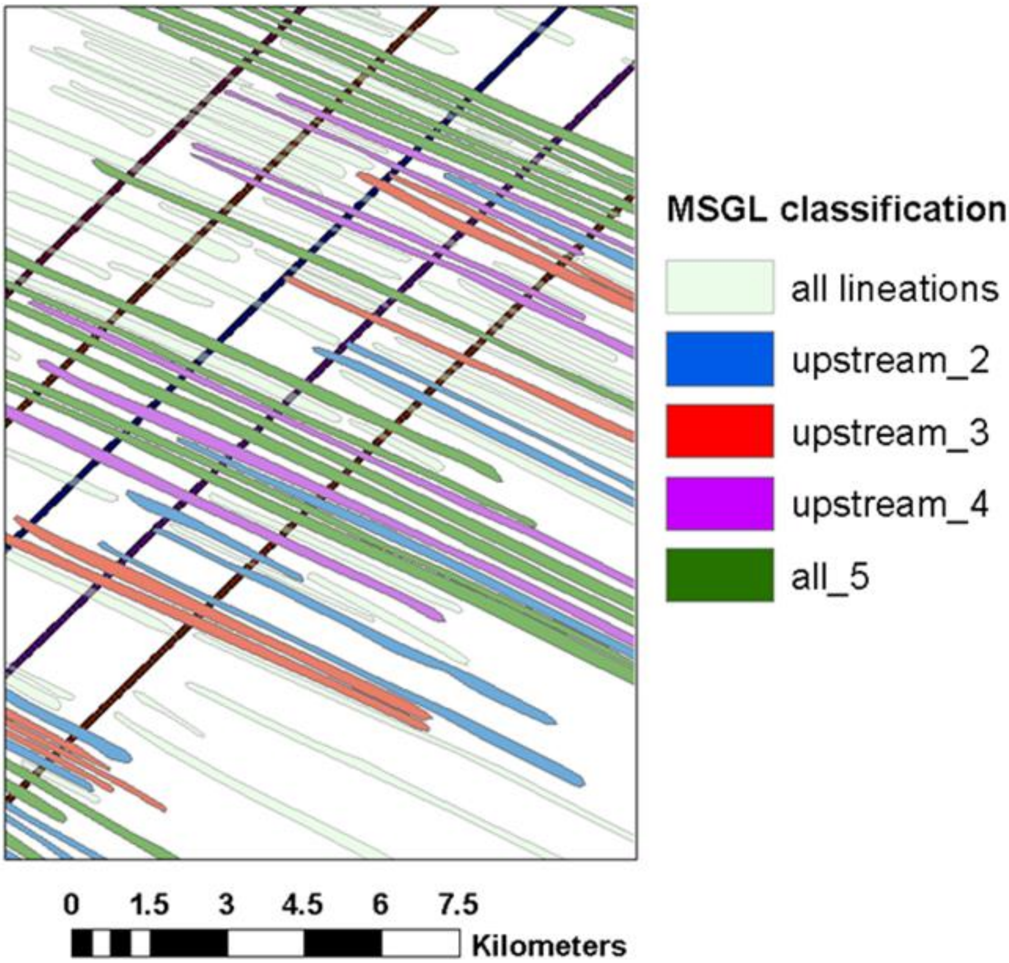

Figure 3.8: *Digitised lineations coloured according to how many transects (including the first, furthest upstream, transect) each lineation passes through. Those lineations coloured green pass through all 5 of the transects, while those coloured purple pass through only the first 4 and so on. Extraction of elevation data was targeted at selecting only the points around lineations passing through the same number of transects.*

In order to analyse lineation elevation it is necessary to first remove the elevation trend that is due to the shape of the trough (Figure 3.9). To detrend the data, polynomial trend lines were fitted to the elevation data and the values produced by these trend lines were subtracted from the elevation data (Figure 3.10 for an example of the detrended data). The choice of what order polynomial to use in the detrending process is one that is judged by the user by visual examination of the fit of the polynomials to the elevation data. Although it was attempted, with reference to the profiles of trough topography and best fit statistics, to keep polynomial order as similar as possible between groups of transects the arbitrary nature of this judgement remains a potential source of error.

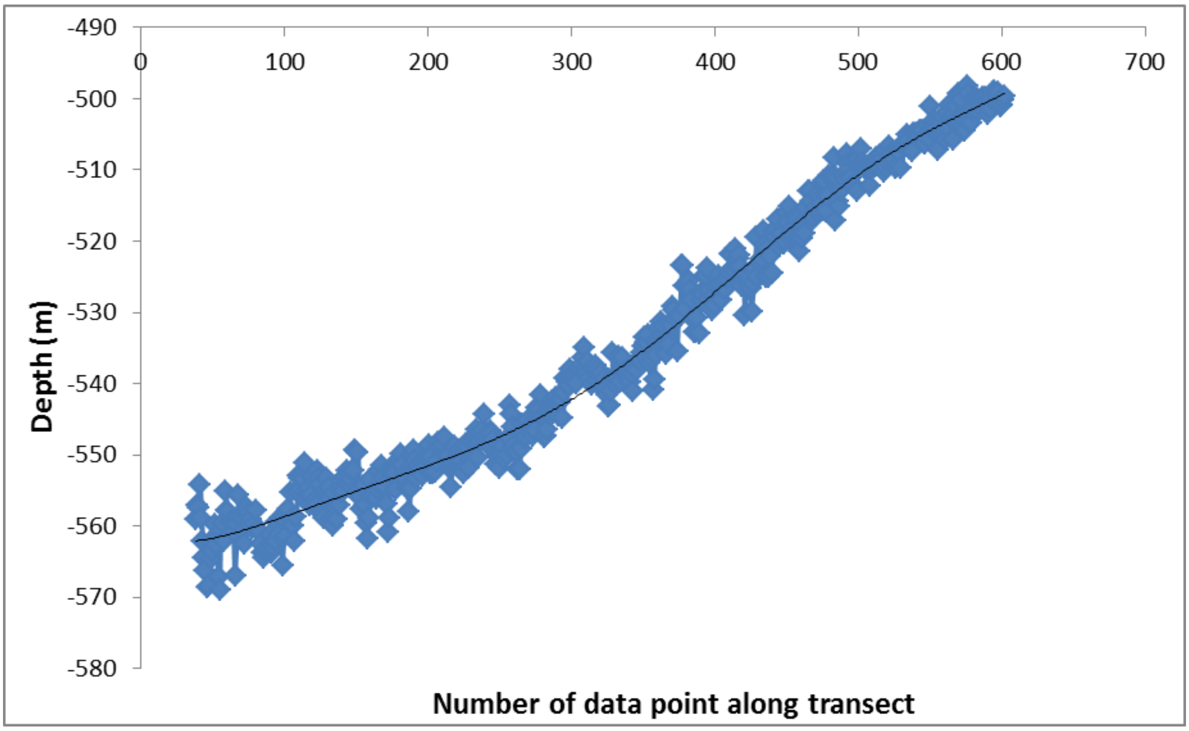

Figure 3.9: *Elevation data extracted from transect. Points along transect (from which elevation data will be extracted) being one pixel width apart. This particular elevation transect has been fitted with a fourth order polynomial trend line.*

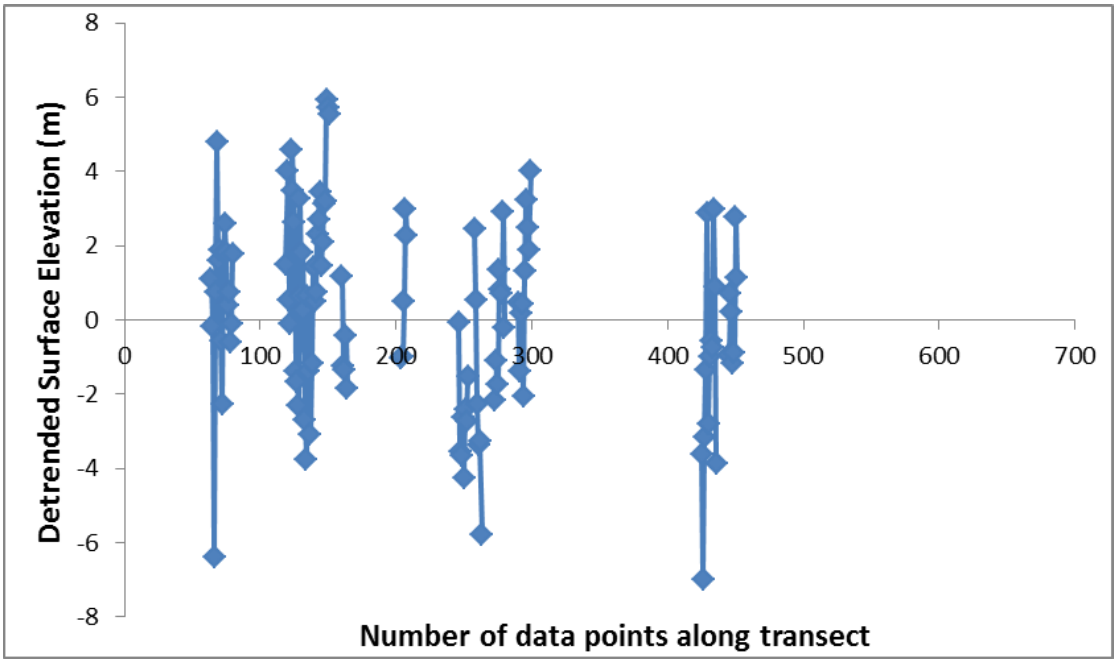

Figure 3.10: *Elevation data (from Figure 3.9) which has been detrended by subtracting the values from the y-values calculated from the polynomial trend line. These particular points have been chosen as they are the areas around digitised lineations which cross the same number of transects within a given group of transects (as shown in Figure 3.8).*

The measure used to characterise the amplitude of the lineations along a transect is the standard deviation of the detrended data. This measure is used as the purpose of the detrending process is to remove the component of elevation change that is due to the shape of the trough. The detrended elevation data (Figure 3.10) is therefore expected to be distributed about 0 m (as if the lineations were situated on a flat surface). This means that the standard deviation of the profile is likely to be an appropriate measure of average lineation amplitude.

It is the nature of this method that it gives only point measurements of lineation elevation with a trade-off between the length of bed a group of transects can cover and the number of lineations analysed by that group. The advantage of this measure, however, is that detrending of elevation data is carried out only along profile lines rather than over the entire area of the palaeo-ice stream bed. The result of this is that the detrending is likely to be more precise and the user is also able to adjust the smoothing by changing the order of the polynomial.

3.6.2. Elevation change along the lineation crests

In order to analyse downstream change in lineation elevation it is ideally necessary to examine elevation values along the crest of each lineation. To do this it is first necessary to account for differences in elevation that are due to the shape of the trough in which the lineations are located. This is done by subtracting the elevation values of a smoothed trough surface from the elevation values from the raw data. Adopting this approach introduces uncertainty with regard to the efficiency of the smoothing process, i.e. has the smoothing process correctly approximated the wider scale topography of the trough. This technique, however, has the advantage that it gives data along the entire length of the lineations, rather than at 1 km intervals, and it deals with individual lineations rather than geographically related groups.

Deterending of the area of the palaeo-ice stream beds used a neighbourhood operator for each pixel, which took the mean value of all pixels within a circle of given radius. The radius chosen determined what scale of features were eliminated from the imagery and as such had to be carefully selected in order to, as much as possible, leave the lineations as the primary remaining geomorphic features. Various radii were tried and the results of the detrending compared to various profiles before a 9 pixel radius was chosen. It remains possible, however, that the detrending process has not performed equally well across the entire area of the palaeo-ice stream beds and in particular that some geomorphic features, like grounding zone wedges, have not been removed.

The lines along which the detrended elevation data will be extracted are those that were used for determining lineation length, derived from lines between the lineation centroid and the lineation endpoints. These lines are used because they provide an approximation of lineation centreline. It is clear, however, that these lines will not necessarily coincide with the crests of the lineations which may cause a problem in determining how lineation amplitude changes downstream. As it is difficult to clearly distinguish where a lineations' crest is, and any discrepancies are likely to be averaged out along the entire length of a lineation, this centreline approximation will be used.

The measure used to determine whether a lineation displays a downstream decrease in elevation is simply taking the mean value of the elevation of the points along the downstream half of the line of extraction away from the mean value of those in the upstream half. It follows that a lineation with a positive value of this measure is displaying morphology consistent with the predictions made by the groove-ploughing theory whereas a negative value would contradict the theory. This method is easier to perform than fitting a regression line to the profile of each individual lineation crest and has the advantage of minimising the potential errors caused by the relatively large vertical uncertainties of much of the imagery used in this project.

3.7. Summary

Examining the morphology of the investigated MSGL populations is the first step in this project. The process of digitising lineations introduces a certain element of the digitiser's judgement but remains the only feasible way to study lineation morphology. The key measures of MSGL morphology (length, width and elongation ratio) will be measured for each population of lineations using the minimum and maximum vertices of the digitised polygons and an approximation of the lineations to rectangles. Although the rectangle approximation is clearly a simplification of lineation morphometry, it is probably appropriate because of the relatively small variations in lineation width along their length.

For the two predictions of the groove-ploughing theory which have been identified as testable, using analysis of lineation morphology, three different tests have been devised. All three of these tests are to some extent limited by the resolution of the imagery and the assumptions regarding lineation morphology which are necessary for their calculation. In particular, the 'lineation crest' method probably relies on more uncertain assumptions than the 'transect' technique although it perhaps has the potential to be, in theory at least, a more comprehensive test of the prediction regarding change in lineation amplitude. Having two alternative measures for lineation amplitude will allow for some comparison of results derived from these different techniques.

4. Results

4.1. Introduction

During this study a total of 19,784 lineations were digitised as polygons from three different palaeo-ice stream beds. Examination of the morphology of the lineation populations from these three palaeo-ice stream beds will be followed by an attempt to test the groove-ploughing formation theory. In Section 3.4 and 3.5 three methods for testing the two, potentially testable, predictions of the theory were outlined and discussed. Comparing the results derived from these methods, for each of the three palaeo-ice stream beds, will be a key part of this chapter.

In this chapter the results from the measurements used to examine the morphology of the MSGL populations will be presented for each site in turn. Comparisons between the morphology of the lineation populations at the separate sites will be followed by analysis of the morphology of the 'global' lineation population (combining all 3 palaeo-ice streams). Similarly, the results from the methods devised to test the groove-ploughing theory will be presented for each palaeo-ice stream bed in turn.

4.2. Dimensions of the Lineation Populations

4.2.1. Dubawnt Lake

In this project lineation digitisation focused on an area of lineations within the 'trunk' (the narrowest part of the identified flowset (Figure 3.1)) of the palaeo-ice stream bed. All lineations within this area were included in digitisation, regardless of dimensions, with a final total of 17,110 polygons. The lineation population was found to be generally quite mixed, with relatively short lineations with low elongation ratios often occurring in close proximity to very elongate lineations.

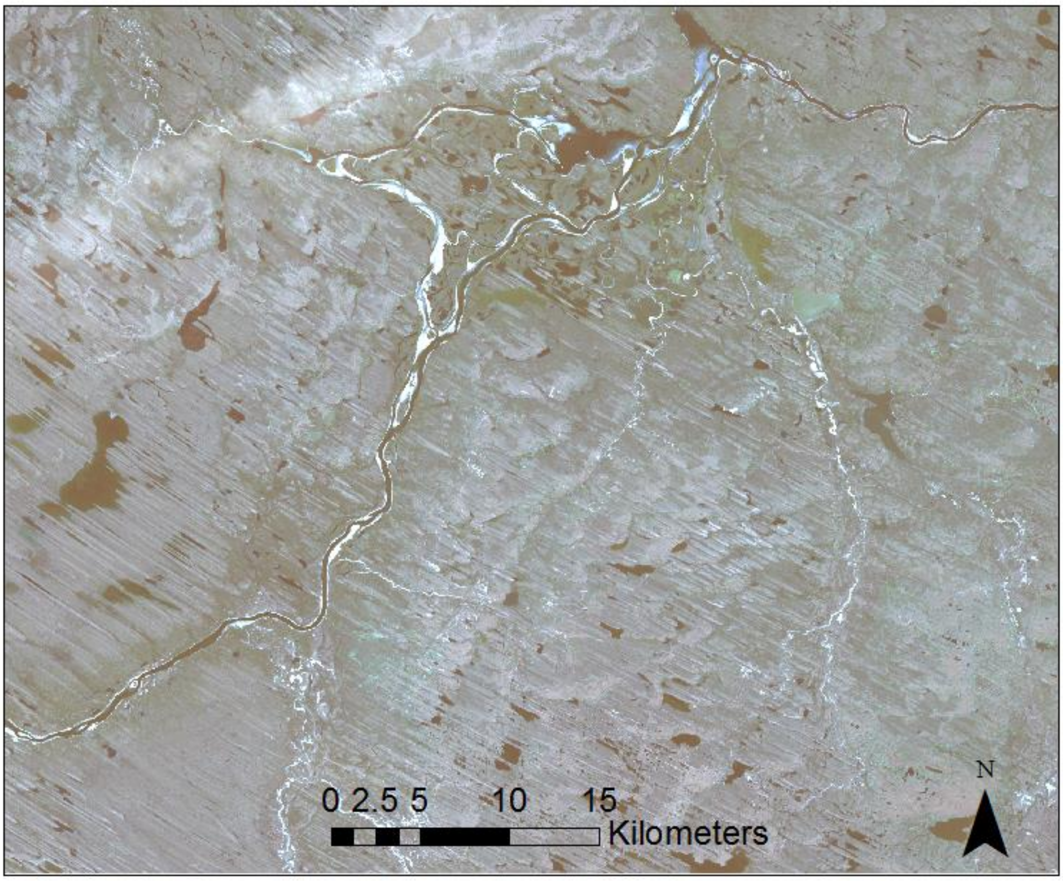

Figure 4.1: *Landsat image of part of the Dubawnt Lake palaeo-ice stream bed (previously studied by Stokes and Clark, 2003 (see Section 3.2.1)). Note that the lineations in the West of the image are considerably more elongate, and are more closely spaced, than those in the North-East of the image.*

The Dubawnt Lake flowset contains areas of lineations with quite different lengths and elongation ratios (as previously noted by Stokes and Clark, 2003). As shown in Figure 4.1, and similarly in Figure 2.3, there are areas of the lineation flowset that contain lineations which are considerably longer and more elongate. In Figures 4.2, 4.3 and 4.4 (below) the lineation length, width and elongation ratio distributions (calculated using the methods described in Section 3.3.1) are displayed.

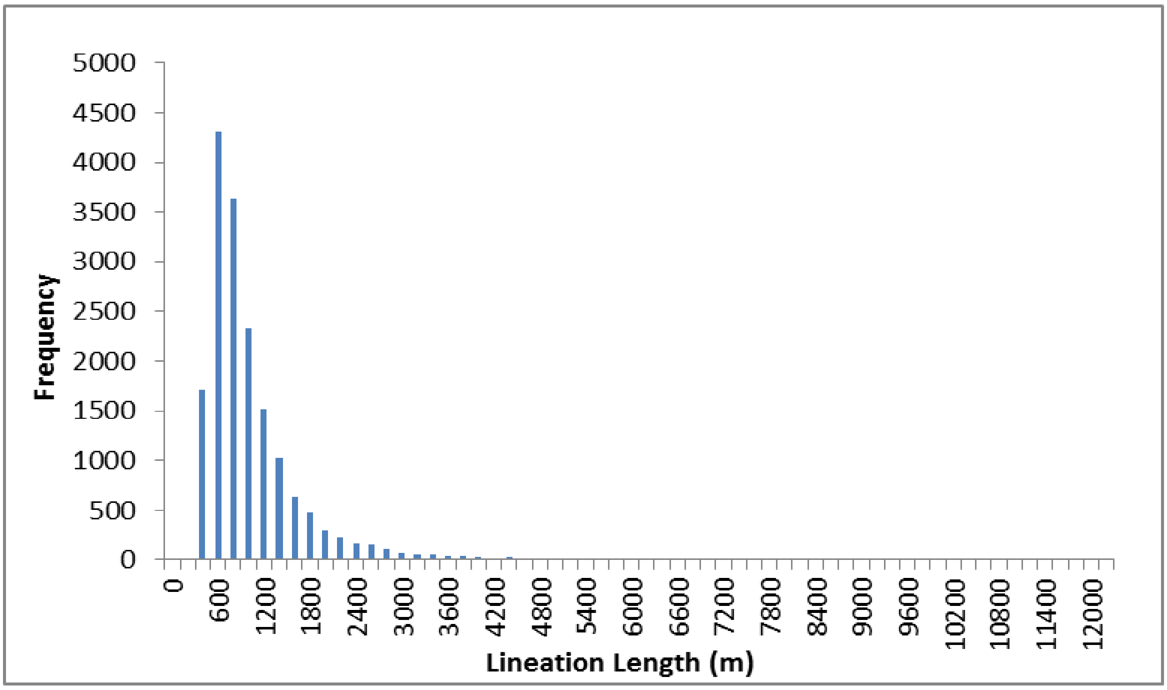

Figure 4.2: *Lineation length histogram for the Dubawnt Lake palaeo-ice stream (bin size 200 m). The measure of lineation length is calculated using lines between the maximum and minimum vertices of the digitised polygons and the lineation centroid.*

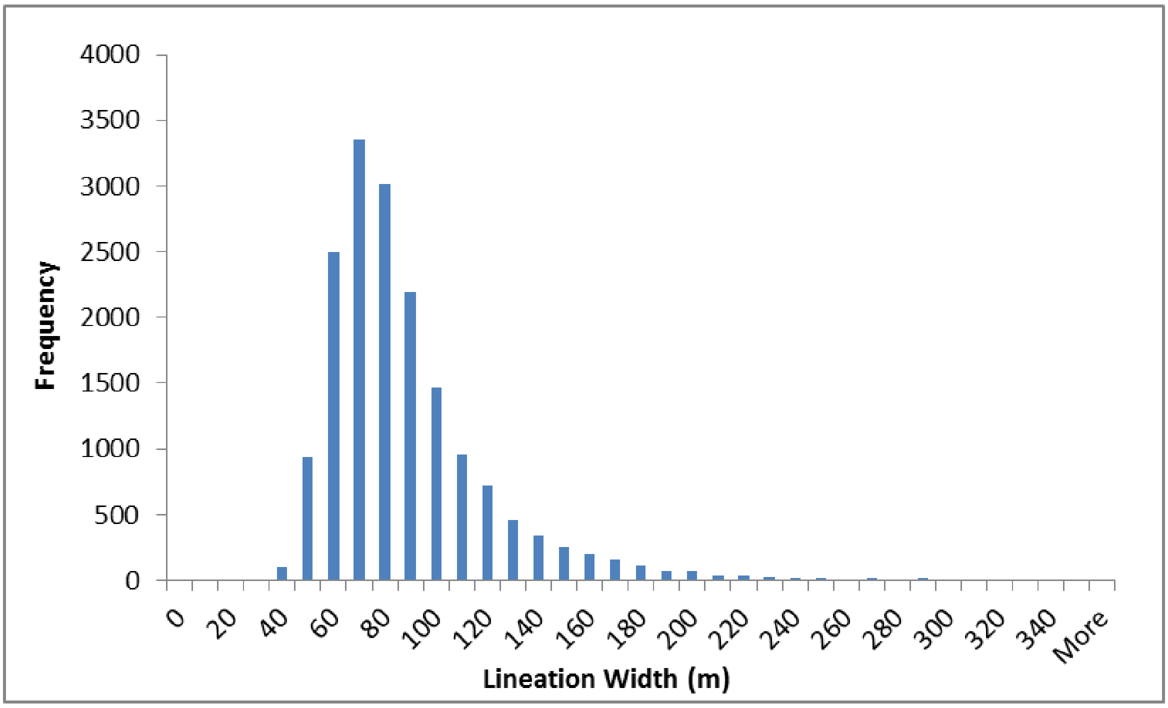

Figure 4.3: *Lineation width histogram for the Dubawnt Lake palaeo-ice stream (bin size 10 m). The measure of lineation width is calculated by dividing lineation area by lineation length: this measure can thus be seen as a measure of average lineation width.*

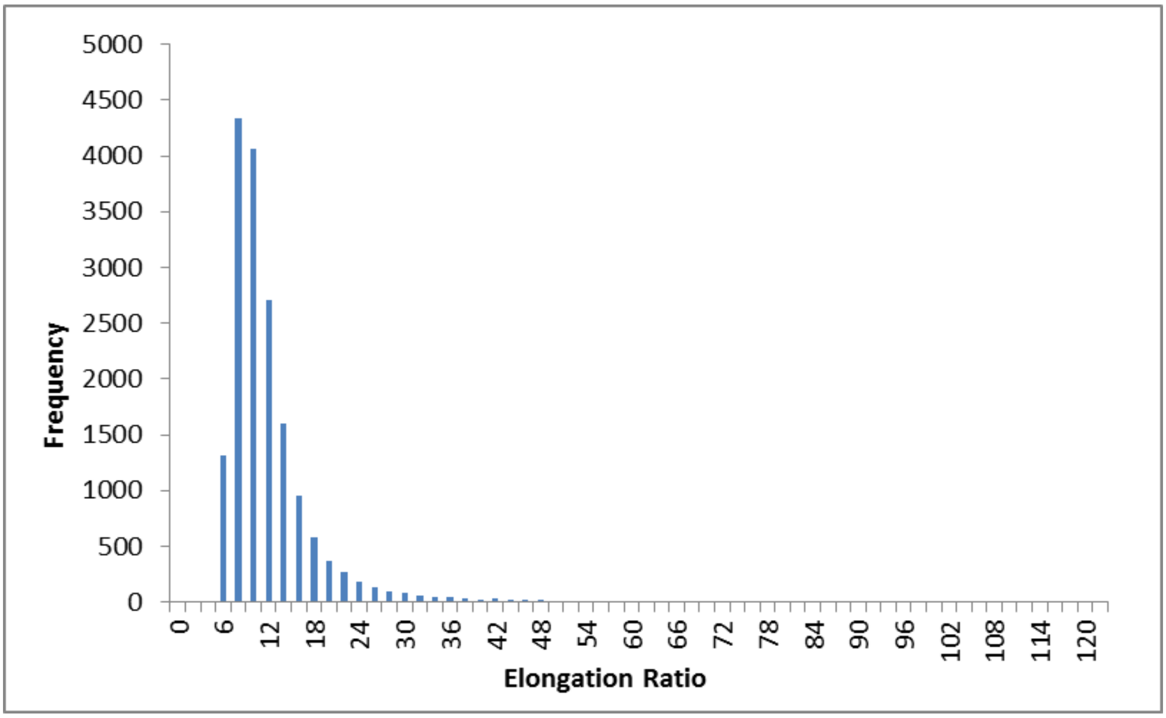

Figure 4.4: *Lineation elongation ratio histogram for the Dubawnt Lake palaeo-ice stream. The elongation ratio is calculated by dividing lineation length by lineation width.*

Histograms of lineation length, width and elongation ratio all show positively skewed unimodal distributions. Median lineation length is 728 m, with a mean value of 961 m, and a maximum value of 20,578 m. Lineation width varies between 28 m and 398 m with a median value of 75 m and a mean value of 84 m. Median lineation elongation ratio is 9.3:1, while the mean value is 11.3:1, with most lineations falling in the range 5-40:1. A small number of extreme elongation ratio values are reported with one lineation reaching 190:1 while the distributions of all three morphological variables display very long tails. Comparison of the three measures of lineation morphology (lineation length, width and elongation ratio) is presented in Figures 4.5, 4.6 and 4.7.

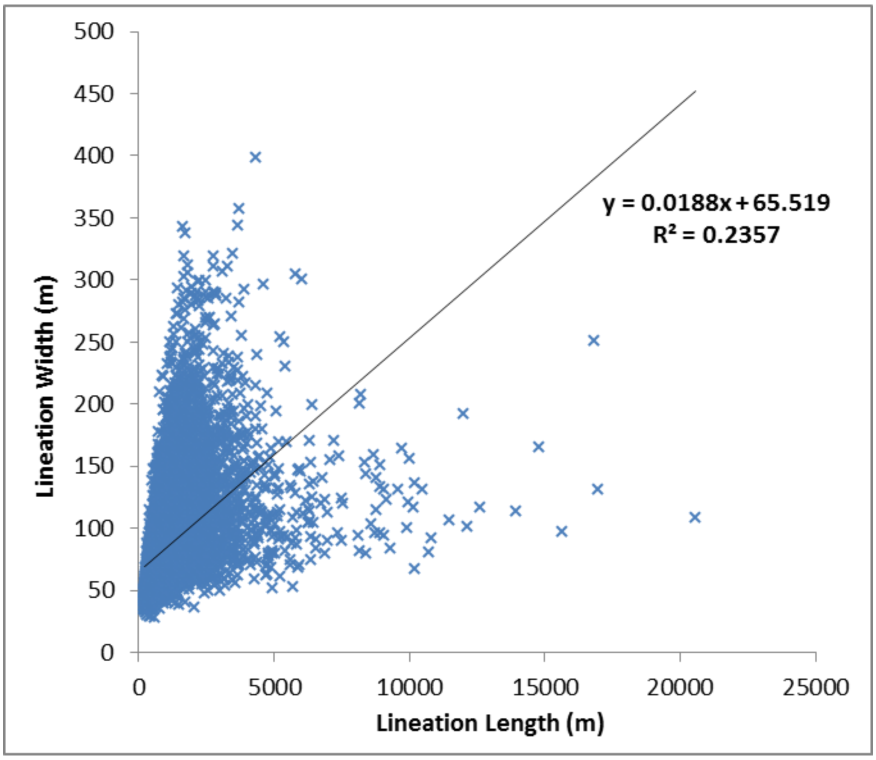

Figure 4.5: *Scatter graph for the Dubawnt Lake lineations showing the relationship between lineation length and width.*

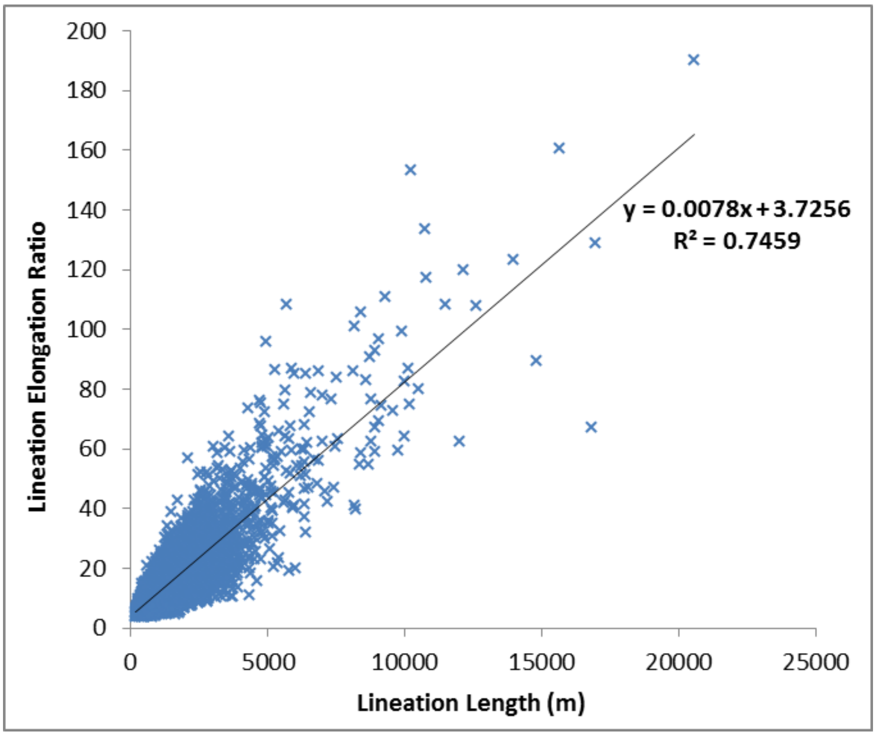

Figure 4.6: *Scatter graph for the Dubawnt Lake lineations showing the relationships between lineation length and elongation ratio.*

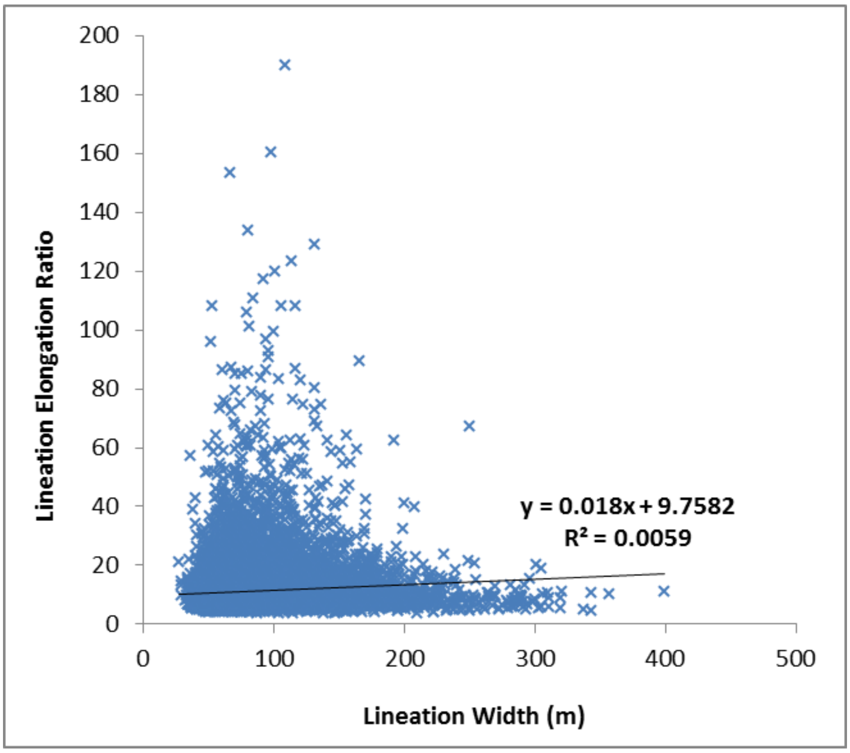

Figure 4.7: *Scatter graph for the Dubawnt Lake lineations, showing the relationships between lineation width and elongation ratio. Note that there is apparently no correlation between the two measures.*

The length to width relationship is only a relatively weak (r^2= 0.24) positive correlation (Figure 4.5). As expected, lineation length is relatively strongly correlated with lineation elongation ratio (r^2= 0.75) with the relationship weakening for very long lineations. Lineation width shows very little correlation with elongation ratio, even when the relative roles of width and length in deriving elongation ratio are considered.

4.2.2. Marguerite Bay

Lineations within the Marguerite Trough palaeo-ice stream bed are, generally, noticeably more elongate than those observed from the Dubawnt Lake palaeo-ice stream bed. It also appears that there is less variation in lineation length and elongation values across the area of the palaeo-ice stream bed than is apparent for the Dubawnt Lake flowset. A number of lineations in the flowset also display different degrees of curvature, this is particularly notable in some of the longer lineations digitised.

A number of lineations (upstream of those digitised) appear to be located immediately downstream of bedrock obstacles, as shown in Figure 4.8. These lineations, emanating from bedrock obstacles, are generally several kilometres in length and have elongation ratios similar to many of the downstream lineations digitised. This area of the palaeo-ice stream bed was not digitised as the lineations were far less densely packed, and generally less elongate, than those downstream. It is, however, notable that the majority of lineations do not have bedrock obstacles at their upstream ends (an observation previously made by Ó Cofaigh *et al*. (2005)).

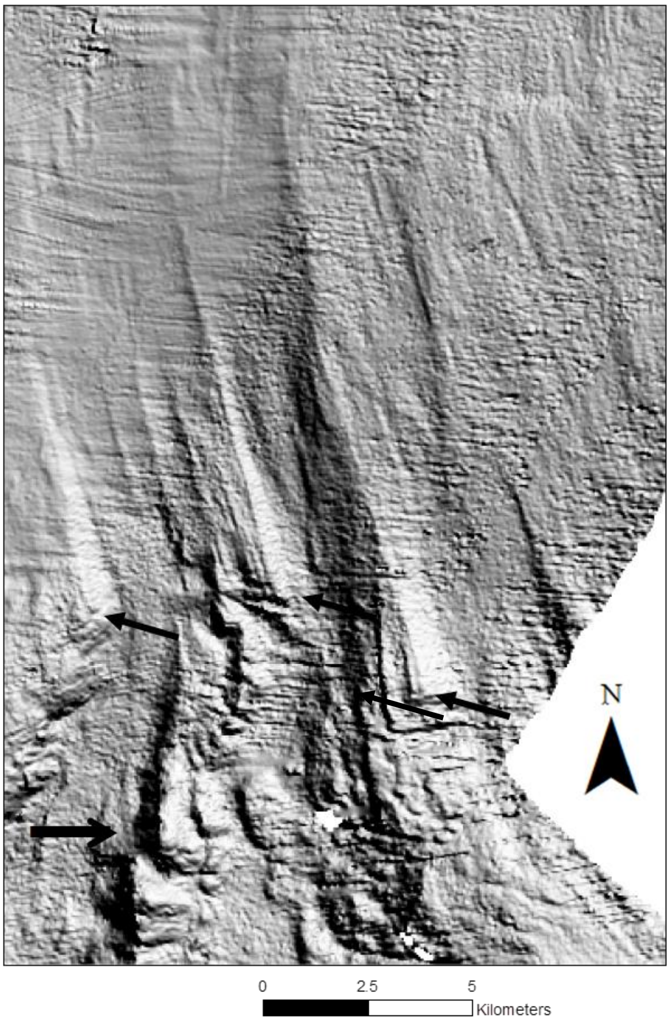

Figure 4.8: *Lineations from an area of the Marguerite Trough palaeo-ice stream bed (upstream of the area of lineations digitised in this project). It is noticeable that a number of these lineations appear to intiate from upstream bedrock roughness elements (arrowed) as noted by Ó Cofaigh et al. (2005).*

The observation of lineation bifurcation and merging (previously mentioned in Section 2.2.3), made by Ó Cofaigh *et al*., (2005), is one that is not likely to be compatible with the groove-ploughing theory. When closely examining the Marguerite Bay palaeo-ice stream, it was not possible to find any single clear-cut example of a lineation that bifurcated or a lineation that merged. It was, however, noted that several groups of closely spaced lineations did appear to decrease in number downstream, but it was not apparent if this was due to lineation merging or simply the termination of a number of the lineations. In the absence of convincing examples of lineation merging and bifurcation, it is not possible to use this particular observation to falsify the groove-ploughing theory. In Figures 4.9, 4.10 and 4.11 (below) the lineation length, width and elongation ratio distributions (calculated using the methods described in Section 3.3.1) are displayed.

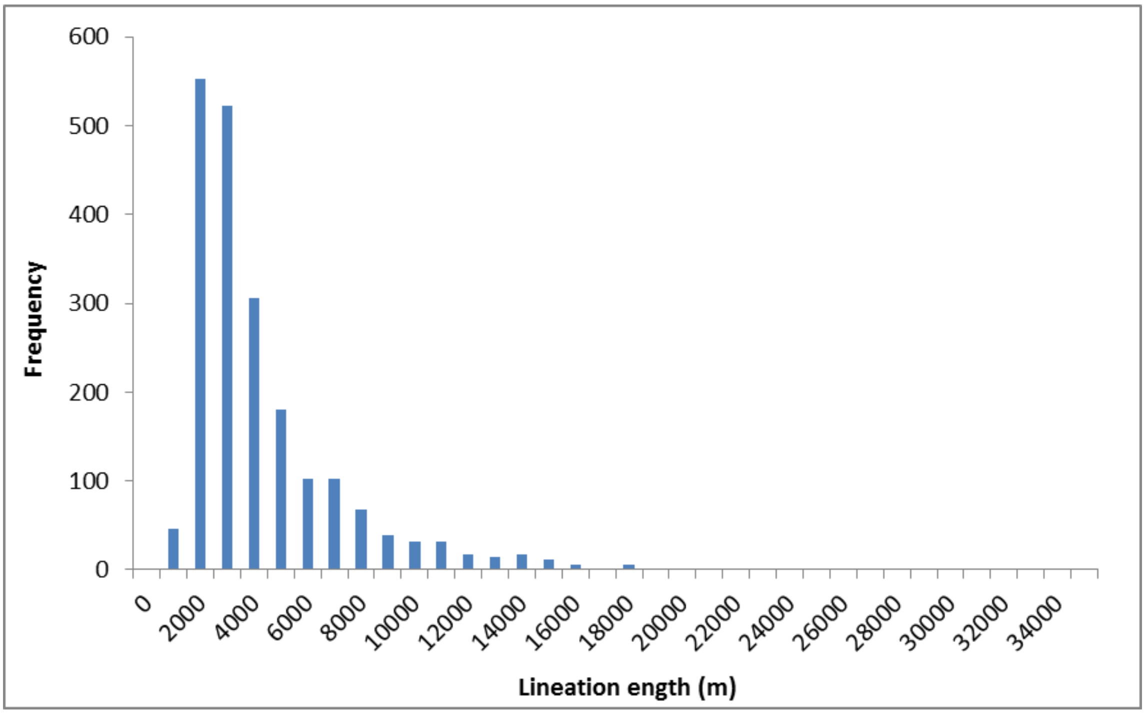

Figure 4.9: *Lineation length histogram for the Marguerite Bay palaeo-ice stream (bin size of 1000 m). The measure of lineation length is calculated using lines between the maximum and minimum vertices of the digitised polygons and the lineation centroid.*

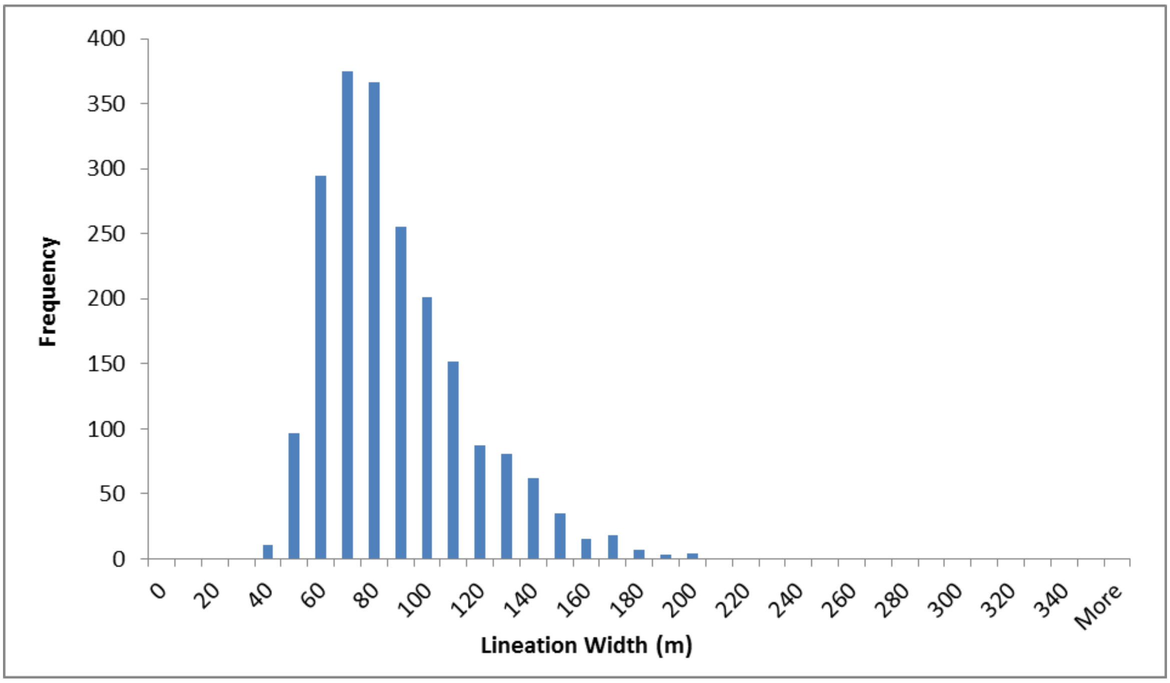

Figure 4.10: *Lineation width histogram for the Marguerite Bay palaeo-ice stream (bin size of 10 m). The measure of lineation width is calculated by dividing lineation area by lineation length: this measure can thus be seen as a measure of average lineation width.*

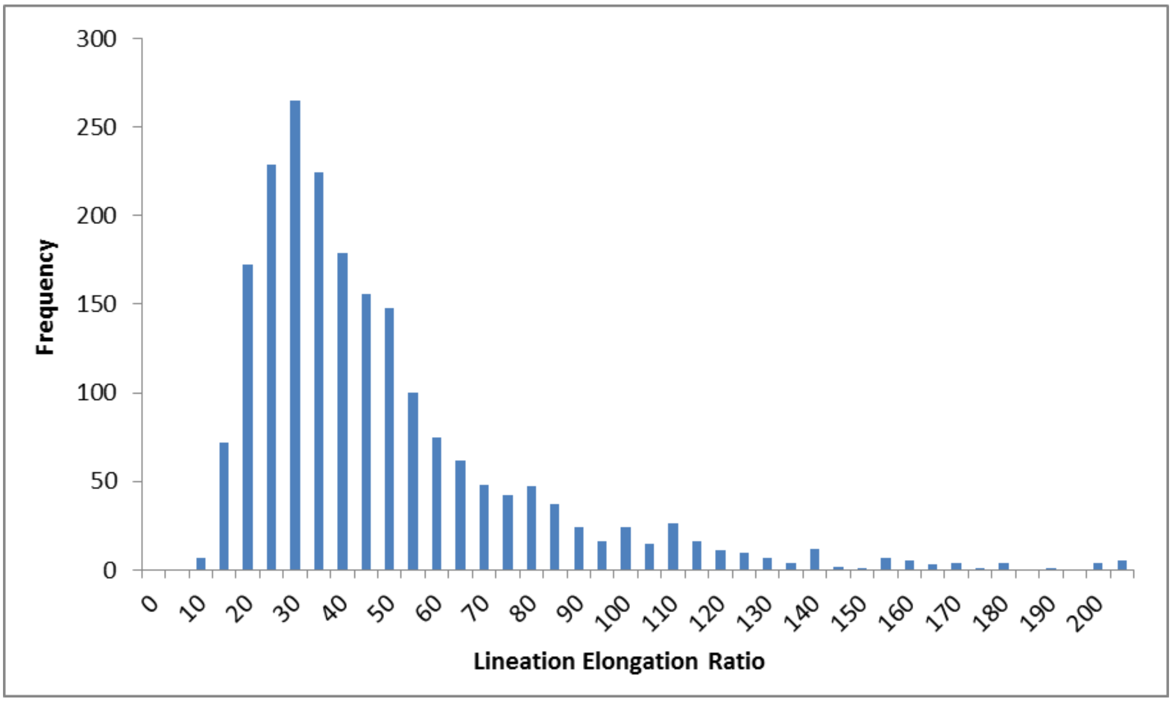

Figure 4.11: *Lineation elongation ratio histogram for the Marguerite Bay palaeo-ice stream. The elongation ratio is calculated by dividing lineation length by lineation width.*

Median lineation length is 2,816 m, with a maximum value of 41,047 m, while lineation width varies between 30 m and 194 m, with a median value of 77 m. Median lineation elongation ratio is 37:1 with most lineations falling in the range 8-120:1. All distributions are, again, relatively long tailed with, in particular, some extremely elongate lineations with ratios in excess of 200:1. Comparison of the three measures of lineation morphology (lineation length, width and elongation ratio) is presented in Figures 4.12, 4.13 and 4.14.

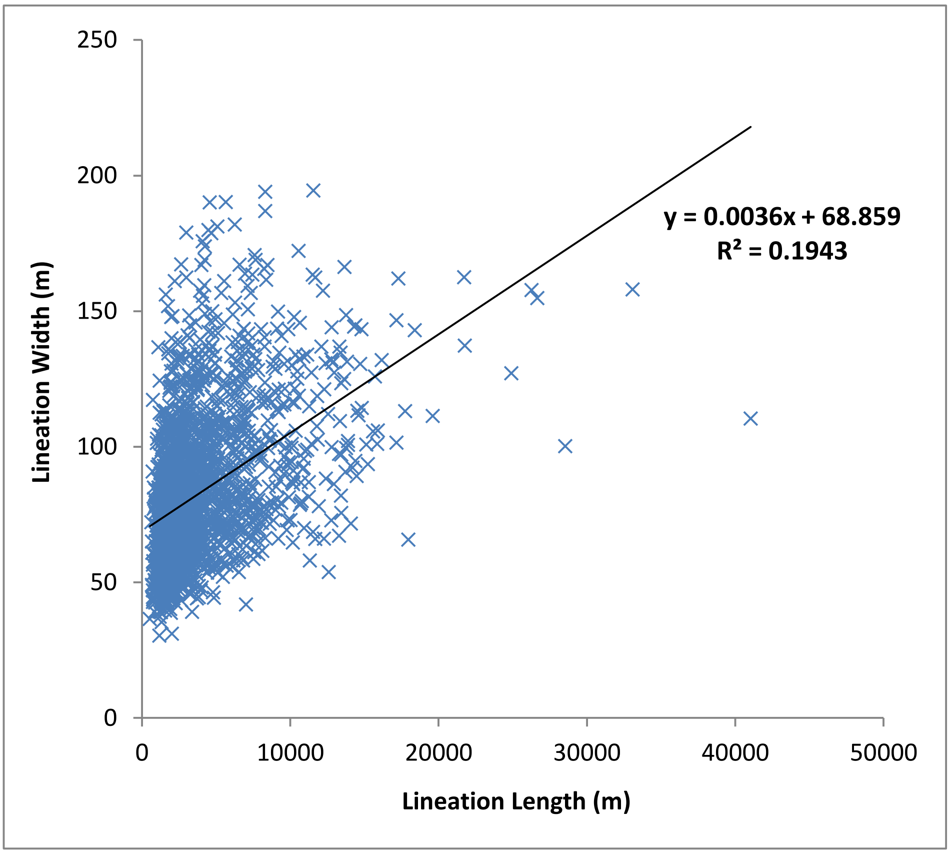

Figure 4.12: *Scatter graph for the Marguerite Bay lineations, showing the relationships between lineation length and lineation width.*

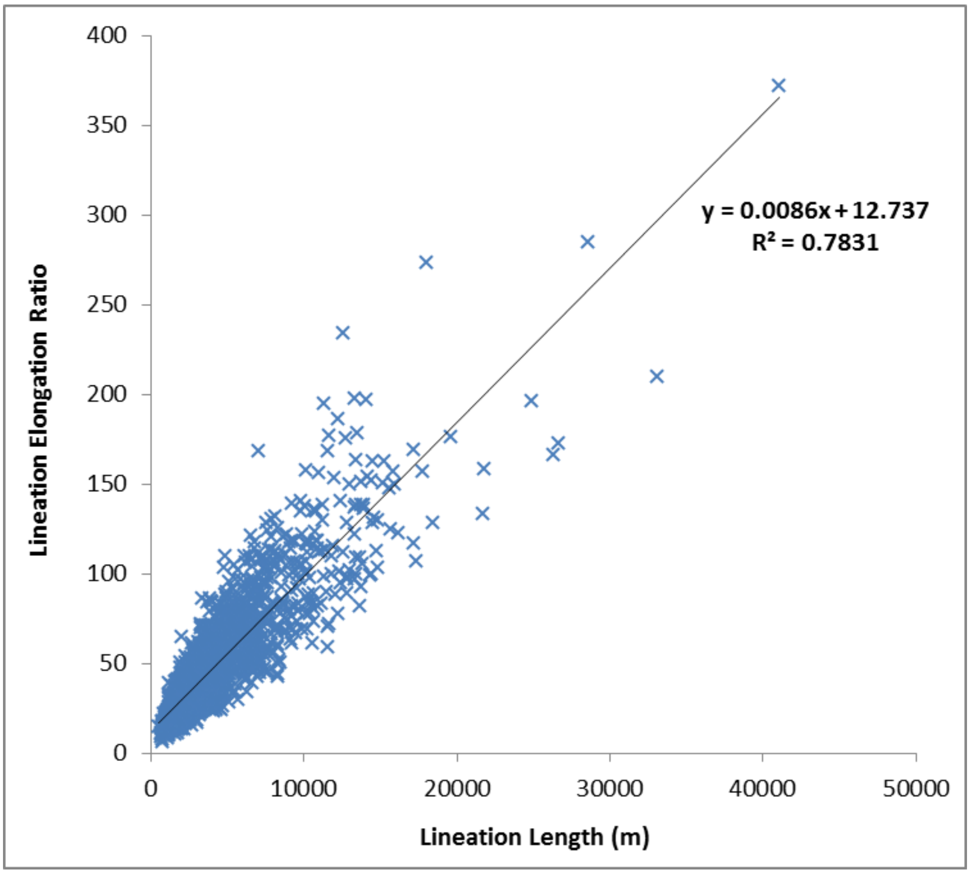

Figure 4.13: *Scatter graph for the Marguerite Bay lineations, showing the relationships between lineation length and lineation elongation ratio.*

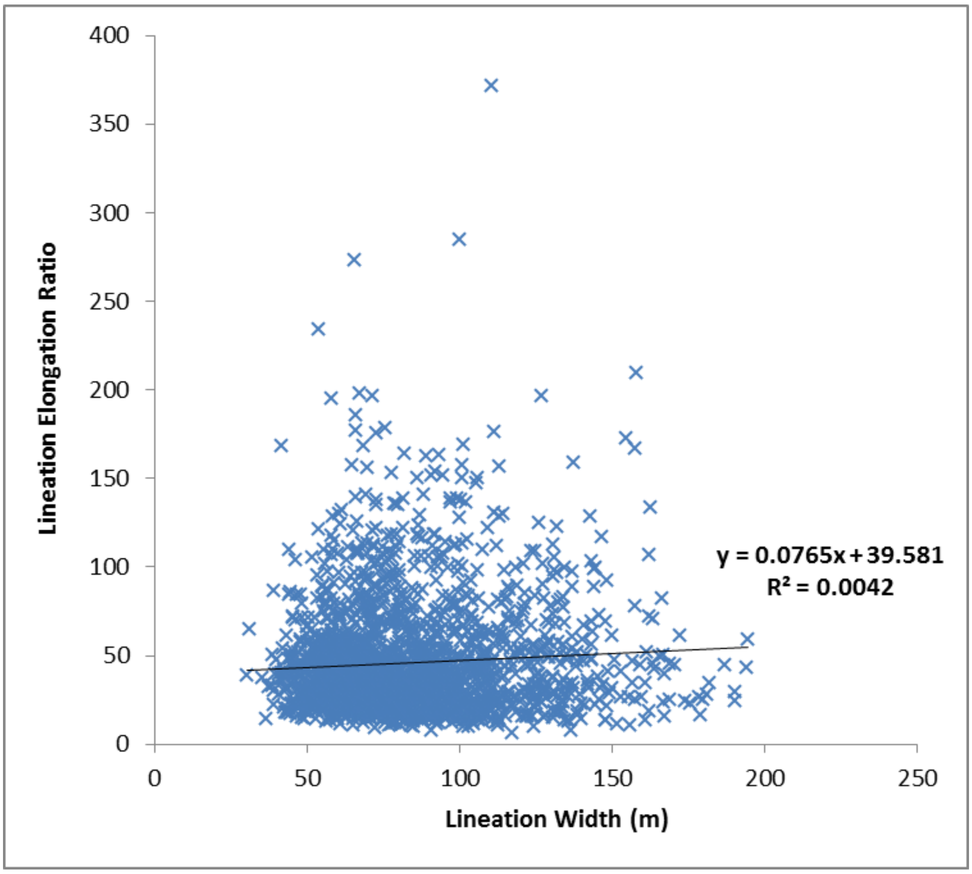

Figure 4.14: *Scatter graph for the Marguerite Bay lineations, showing the relationships between lineation width and lineation elongation ratio.*

Examination of the relationships between length, width and elongation ratio (Figure 4.12, 4.13 and 4.14), shows them to be relatively similar to those found for the Dubawnt Lake palaeo-ice stream. Correlation between the length and width variables is relatively weak, with many lineations of relatively short length displaying some of the highest width values. Elongation ratio is also, unsurprisingly, much more strongly correlated with lineation length than lineation width.

4.2.3. Malangsdjupet:

All lineations within the Malangsdjupet trough (a total of 301) were digitised. In general, these lineations appeared to be similar in length to those observed from the Marguerite Bay palaeo-ice stream flowset. The Malangsdjupet trough is, however, considerably smaller than the Marguerite Bay trough and hence has a smaller lineation population and potentially provides less space for lineations to lengthen. In the central area of the trough a bathymetric high was observed which was not overprinted by lineations and may have acted to further constrain lineation growth.

It was notable that a large number of the lineations near the head of the trough appeared to be asymmetrical. No major bedrock roughness was, however, unequivocally visible from any part of the trough. In addition to the lineations digitised, a small number of relatively long, flow parallel, features, at or near the trough margins, were noted. Some of these flow parallel features may well have been shear margin moraines rather than lineations.

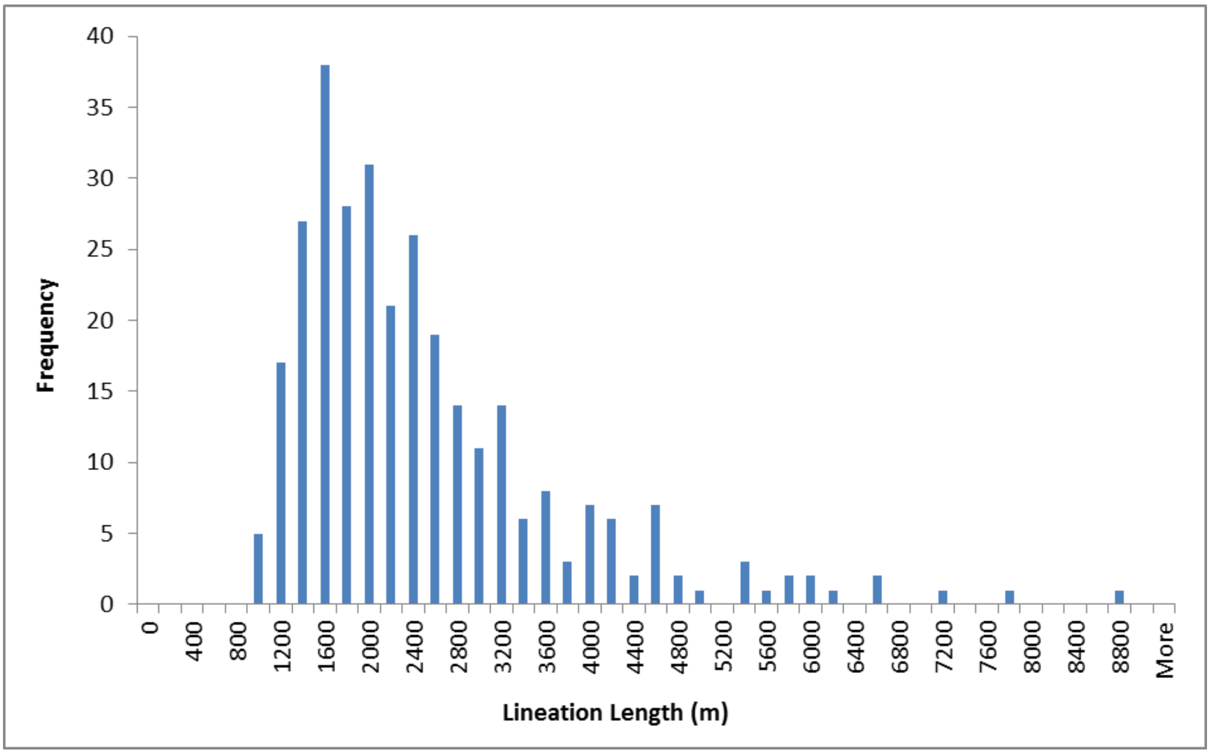

Figure 4.15: *Lineation length histogram for the Malangsdjupet palaeo-ice stream (bin size of 200 m).*

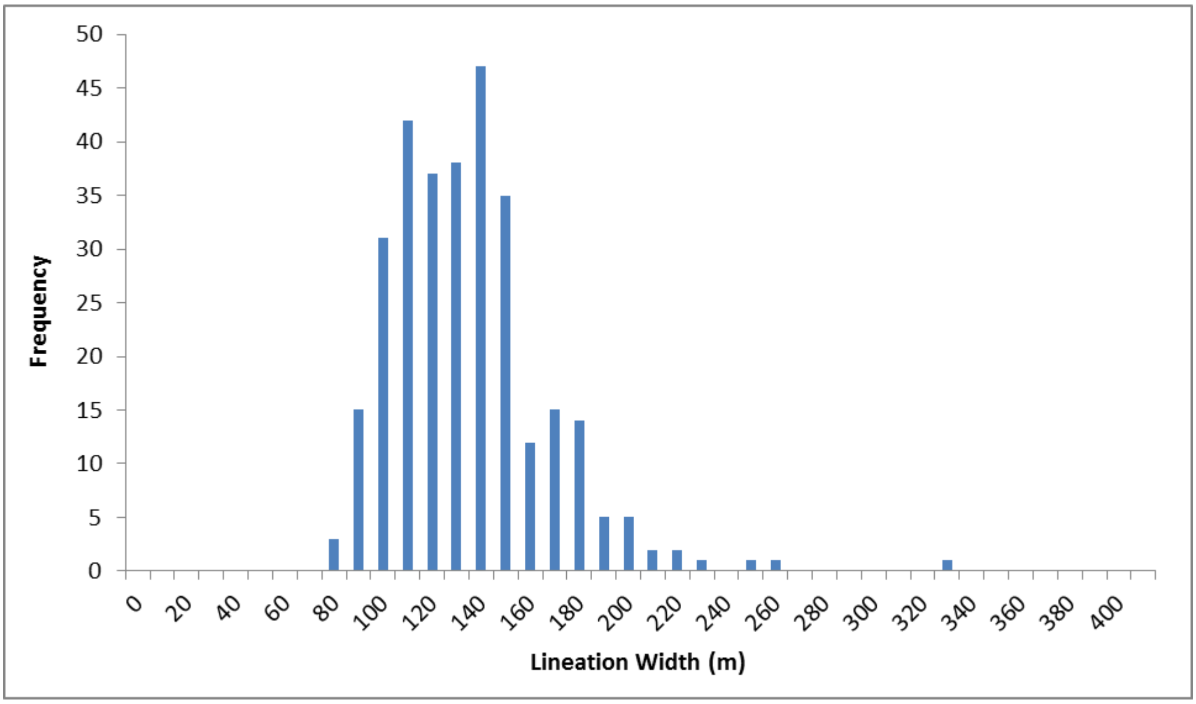

Figure 4.16: *Lineation width histogram for the Malangsdjupet palaeo-ice stream (bin size of 10 m).*

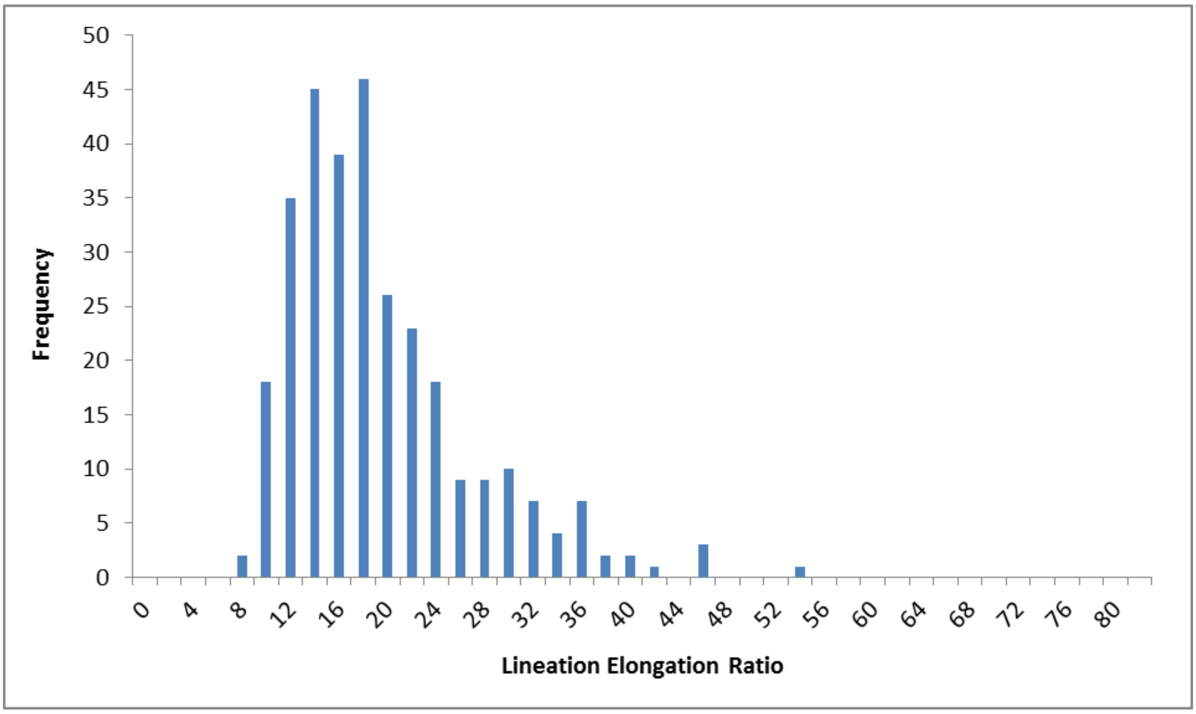

Figure 4.17: *Lineation elongation ratio histogram for the Malangsdjupet palaeo-ice stream.*

The lineation length, width and elongation ratio distributions (Figures 4.15, 4.16 and 4.17) are, again, all positively skewed and unimodal. It is, however, apparent that the lineation width distribution (Figure 4.16) displays a relatively steep falling limb compared to the lineation length and elongation ratio distributions as well as the lineation width distributions for Dubawnt Lake and Marguerite Bay. Median lineation length is 2,091 m, with a maximum value of 8,642 m, while lineation width varies between 74 m and 320 m, with a median value of 126 m. Median lineation elongation ratio is 17:1 with most lineations falling in the range 8-40:1. Comparison of the three measures of lineation dimensions (lineation length, width and elongation ratio) is presented in Figures 4.18, 4.19 and 4.20.

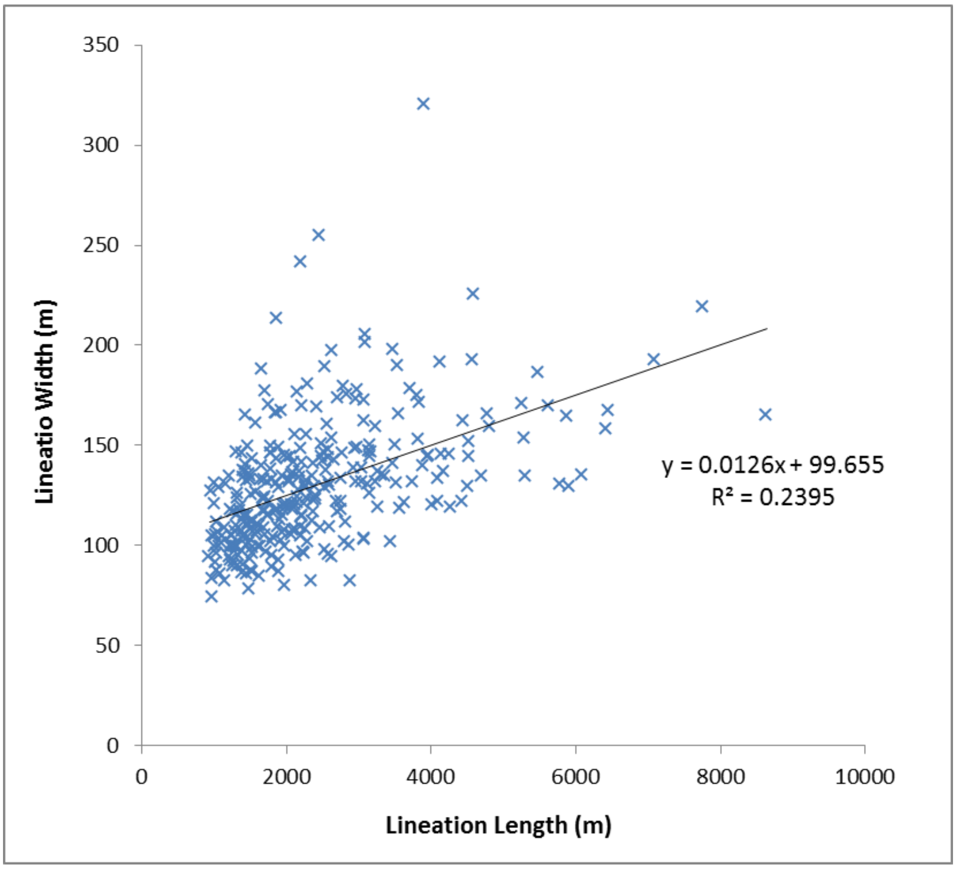

Figure 4.18: *Scatter graph for the Malangsdjupet lineation population (n=301), showing the relationships between lineation length and lineation width.*

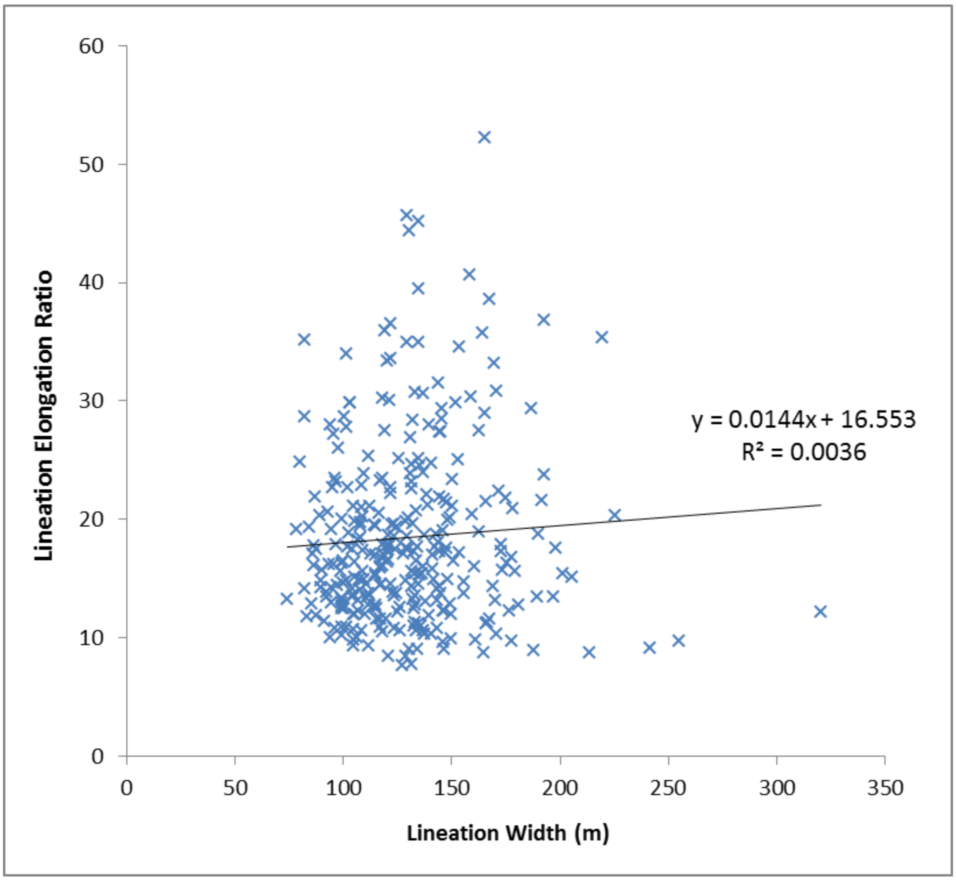

Figure 4.19: *Scatter graph for the Malangsdjupet lineation population (n=301), showing the relationships between lineation width and elongation ratio. Lineation elongation ratio is found to be relatively poorly correlated with lineation length.*

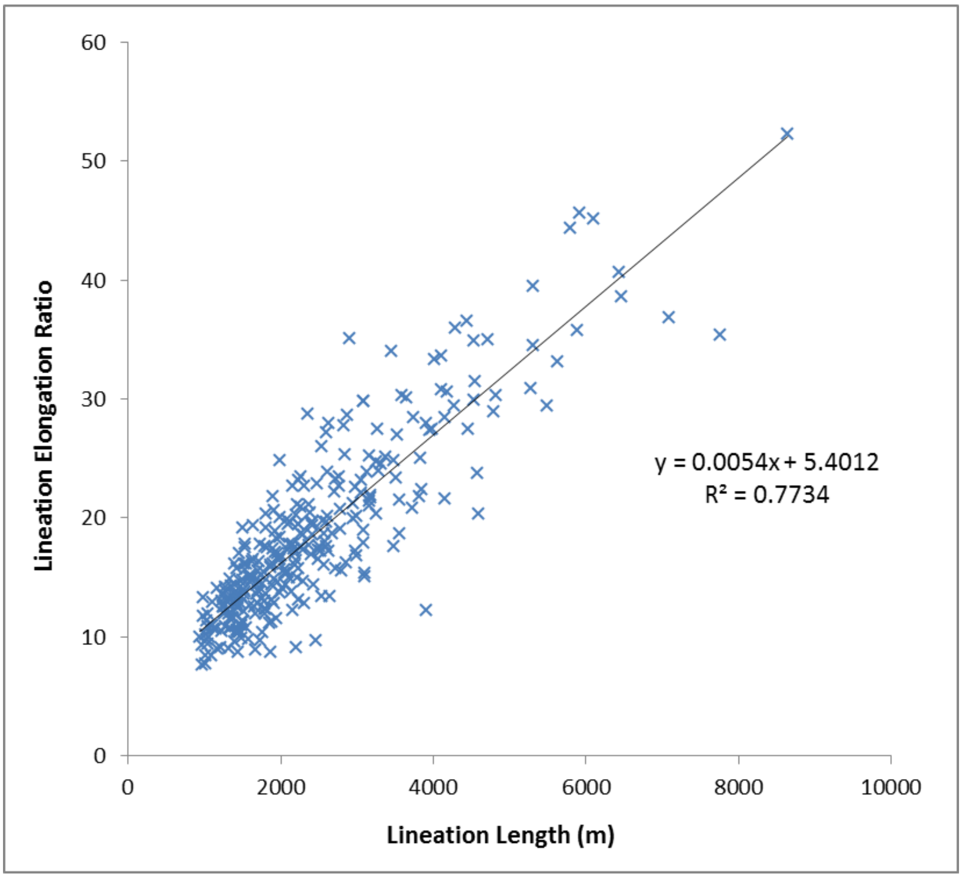

Figure 4.20: *Scatter graph for the Malangsdjupet lineation population (n=301), showing the relationships between lineation length and elongation ratio. Again lineation ER is found to be relatively strongly (positively) correlated with lineation length.*

Examination of the relationships between lineation length, width and ER (Figures 4.18, 4.19 and 4.20) shows them to be relatively similar to those found for the other two palaeo-ice streams. Lineation length and width are again relatively poorly correlated with some of the widest lineations having relatively short lengths. Lineation ER is, once again, most strongly correlated with lineation length.

4.3. Morphology of the 'global' MSGL population:

In the previous section, the morphological characteristics of each lineation population were examined in turn. The digitisation of 19,784 lineations from 3 different palaeo-ice stream beds, however, also gives an opportunity to both compare lineation populations and to analyse the characteristics of the entire

MSGL population. This section will present an analysis of the length, width and elongation ratio distributions for each palaeo-ice stream bed followed by presentation of the combined ‘global’ distributions. Comparison of the lineation length distributions of all three palaeo-ice streams is presented in Figures 4.21 and 4.22 and Table 4.1.

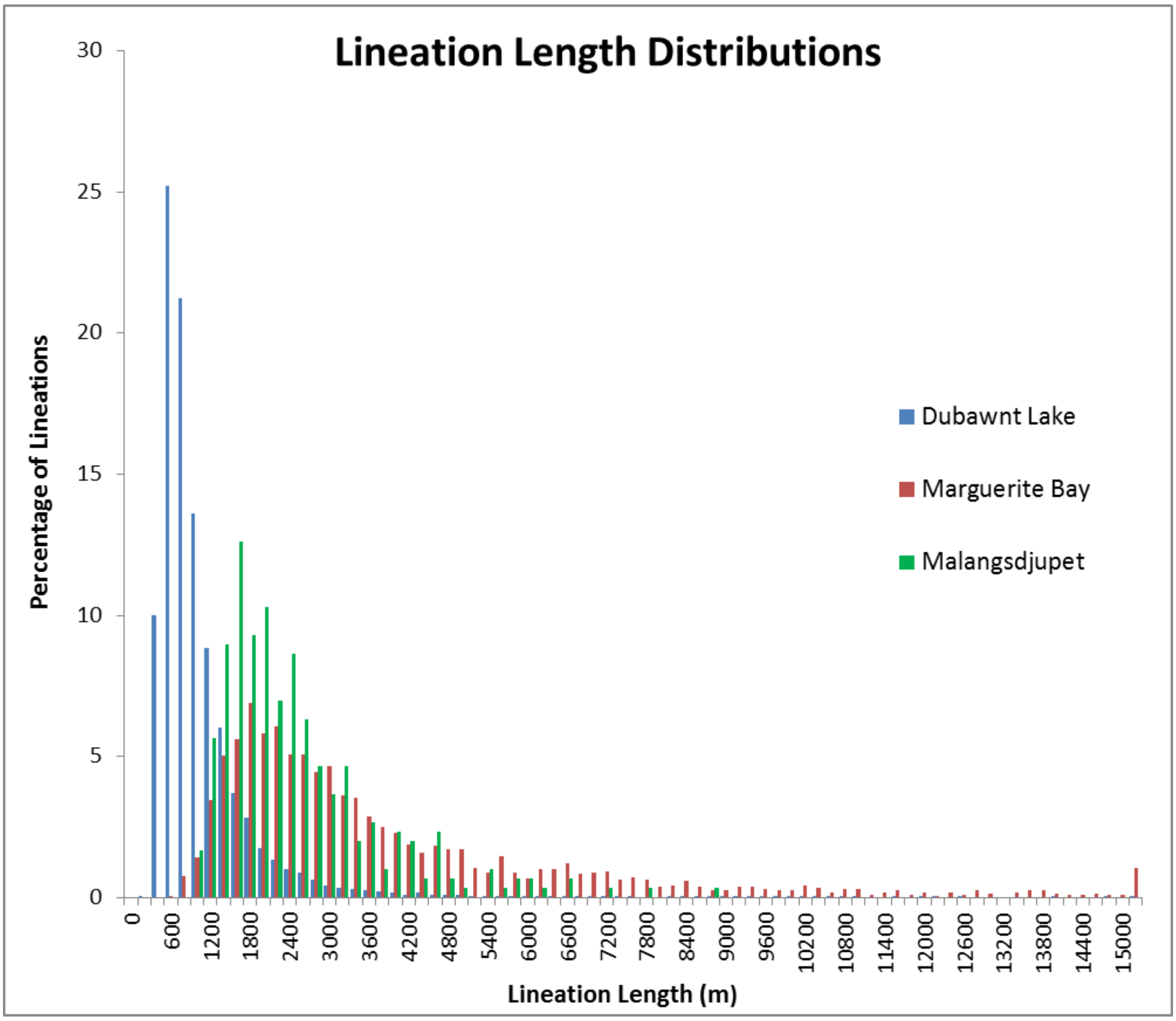

Figure 4.21: *Histogram displaying the lineation length distributions for the three palaeo-ice stream beds mapped in this study. Note that the Dubawnt Lake distribution’s modal class is located at a much lower length value than either of the other palaeo-ice stream beds, although all three distributions are long-tailed with a small number of very long lineations.*

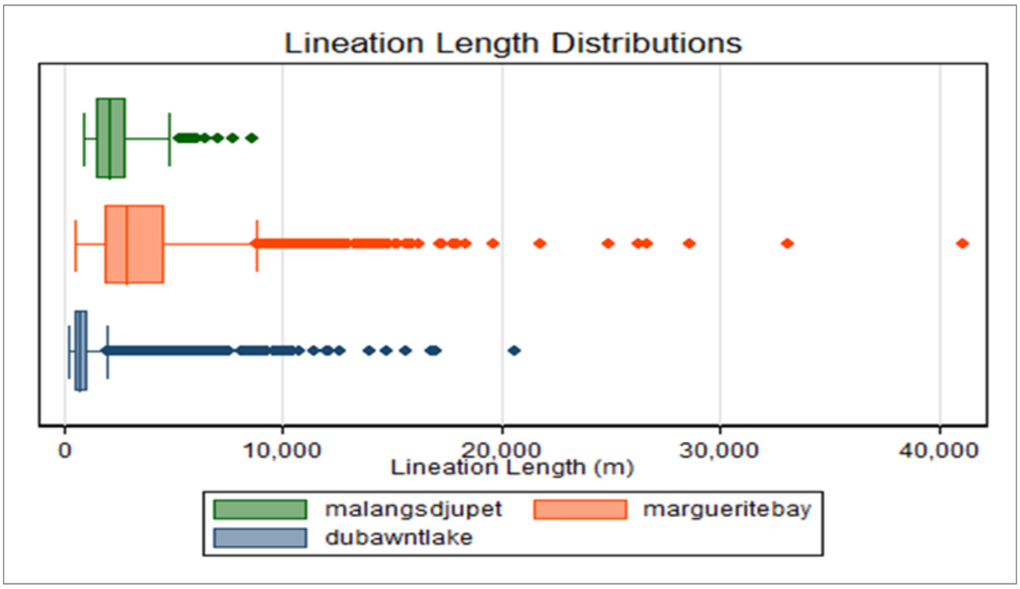

Figure 4.22: *Box plots comparing the lineation length distributions for the three palaeo-ice stream beds mapped. The boxes enclose the 25th to the 75th percentile, with the median represented by the central line, while the whiskers represent the 5th and 95th percentiles. The dots represent data values outside of the 5-95th percentile range.*

Table 4.1: *Summary statistics on lineation length from the three palaeo-ice stream beds.*

	Dubawnt Lake	Marguerite Bay	Malangsdjupet
Number of Lineations	17,110	2,065	307
Minimum (m)	196	533	942
25th Percentile (m)	521	1,863	1,524
Median (m)	728	2,816	2,091
Mean (m)	961	3,862	2,408
75th Percentile (m)	1,104	4,639	2,888
Maximum (m)	20,578	41,047	8,641
Inter Quartile Range (m)	583	2,776	1,363
Range (m)	20,382	40,514	7,699
Standard Deviation (m)	863	3,264	1,234
Skewness	6.0	3.2	1.8
Kurtosis	68.6	18.1	4.0

All three palaeo-ice stream beds display long tailed, unimodal, length distributions (Figures 4.21 and 4.22) with all beds having some very long lineations (reaching 41 km for Marguerite Bay). Both Malangsdjupet and Marguerite Bay (2,091 m and 2,816 m respectively) have higher median lengths than Dubawnt Lake (728 m). Similarly Marguerite Bay (2,776 m) has a considerably higher interquartile range (IQR) than either Dubawnt Lake or Malangsdjupet (583 m and 1,363 m respectively).

Graphs comparing lineation width distributions are presented in Figures 4.23 and 4.24 (below) and summary lineation width statistics are provided in Table 4.2.

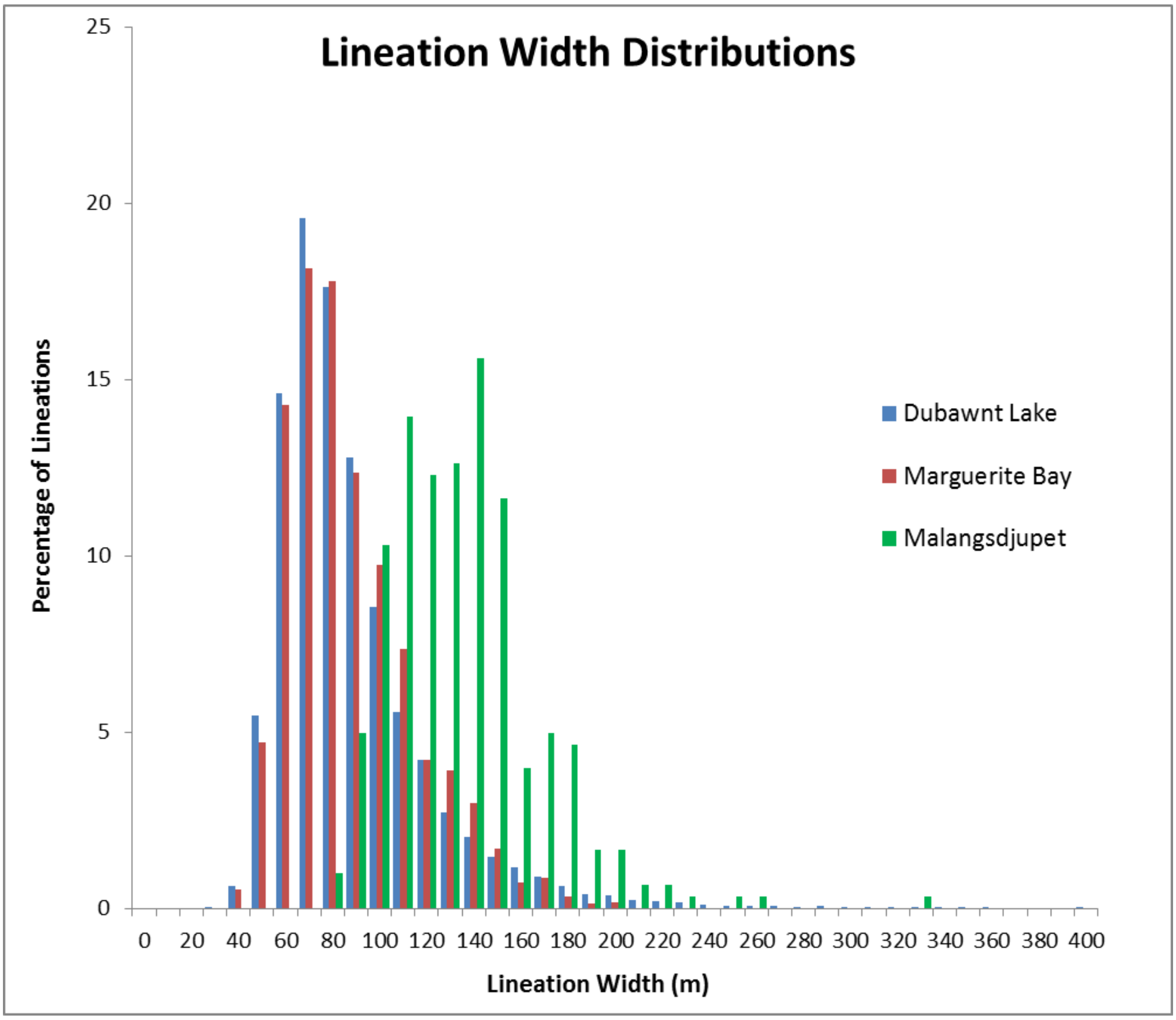

Figure 4.23: *Bar graph displaying the lineation width distributions for the three palaeo-ice stream beds mapped in this study. Note that the Dubawnt Lake and Marguerite Bay distributions are extremely similar.*

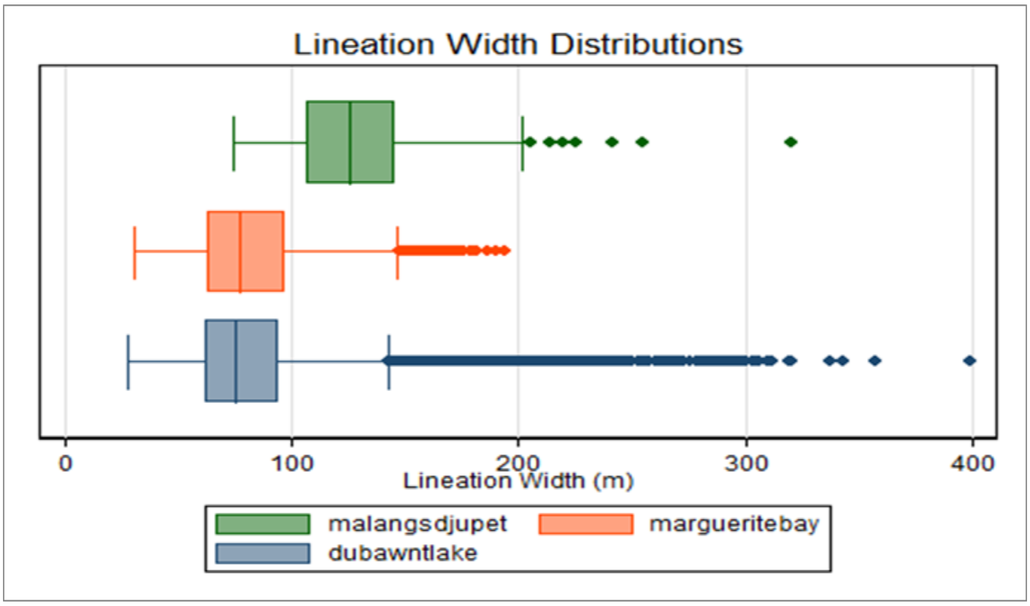

Figure 4.24: *Box plots comparing the lineation width distributions for the three palaeo-ice stream beds mapped. The boxes enclose the 25th to the 75th percentile, with the median represented by the central line, while the whiskers represent the 5th and 95th percentiles.*

Table 4.2: *Summary statistics on lineation width from all three palaeo-ice streams.*

	Dubawnt Lake	**Marguerite Bay**	**Malangsdjupet**
Number of Lineations	17,110	2,065	307
Minimum (m)	28	30	74
25th Percentile (m)	62	63	107
Median (m)	75	77	126
Mean (m)	84	83	130
75th Percentile (m)	94	97	145
Maximum (m)	399	194	320
Inter Quartile Range (m)	32	34	38
Range (m)	371	164	246
Standard Deviation (m)	33	27	32
Skewness	2.2	1.1	1.4
Kurtosis	8.1	1.1	4.7

The lineation width distributions for the Dubawnt Lake and Marguerite Bay palaeo-ice streams (Figures 4.23 and 4.24) are extremely similar, unimodal and long tailed, with median width values of 75 m and 77 m respectively. The Malangsdjupet width distribution, however, has a higher median width value

(126 m) and a slightly higher IQR (38 m compared to 32 m and 34 m). This may partially be attributed to the smaller sample size for Malangsdjupet (n= 307) compared to Dubawnt Lake (n= 17,110) and Marguerite Bay (n= 2,065).

Comparison of lineation elongation ratio distributions, from all three palaeo-ice streams, is presented in Figure 4.25 and Figure 4.26 while summary statistics are presented in Table 4.3.

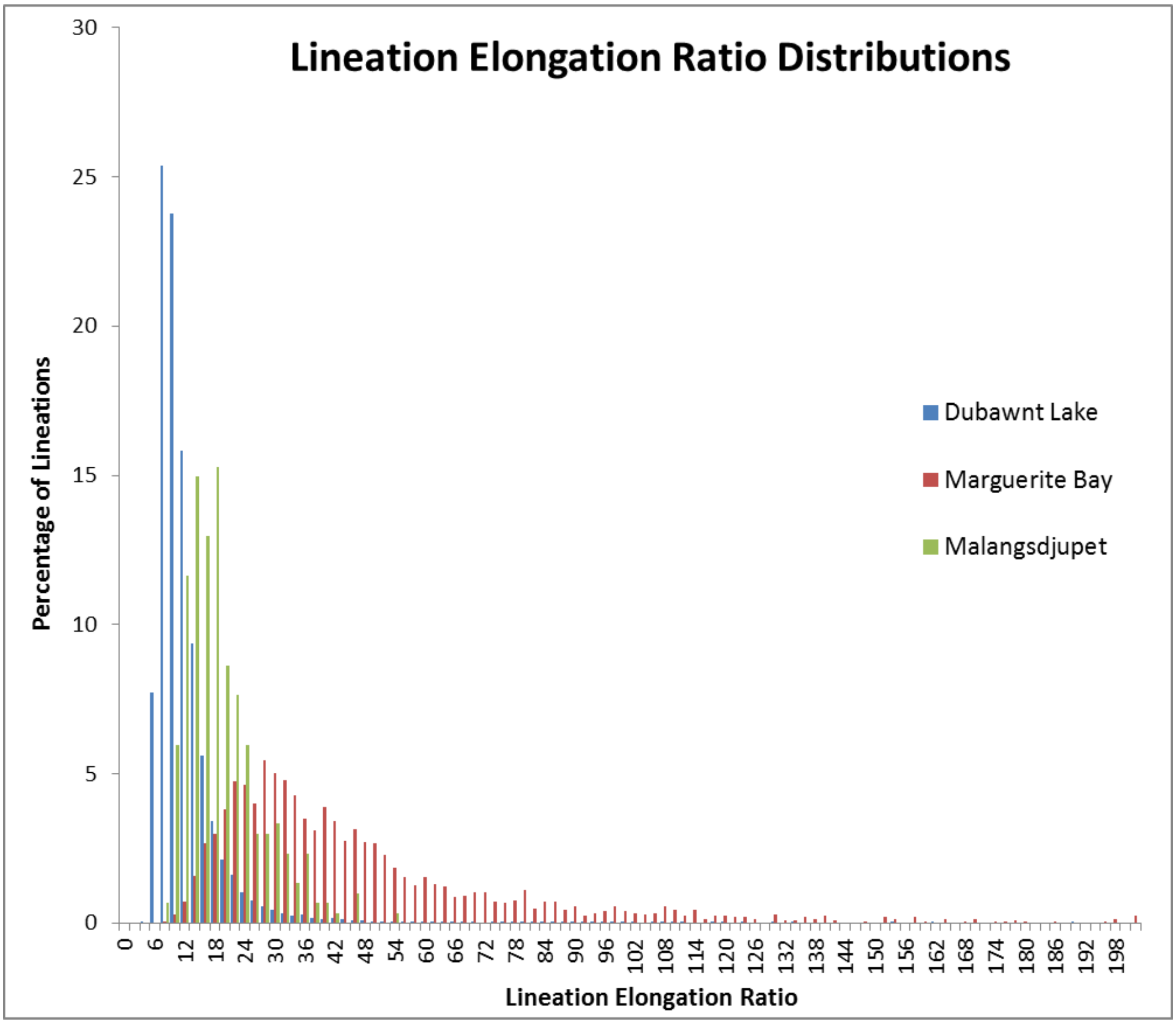

Figure 4.25: *Bar graph showing the lineation elongation ratio distributions for all three of the palaeo-ice stream beds mapped. While the three distributions overlap, it is evident that each has a quite different modal class and distinctly different spread of values.*

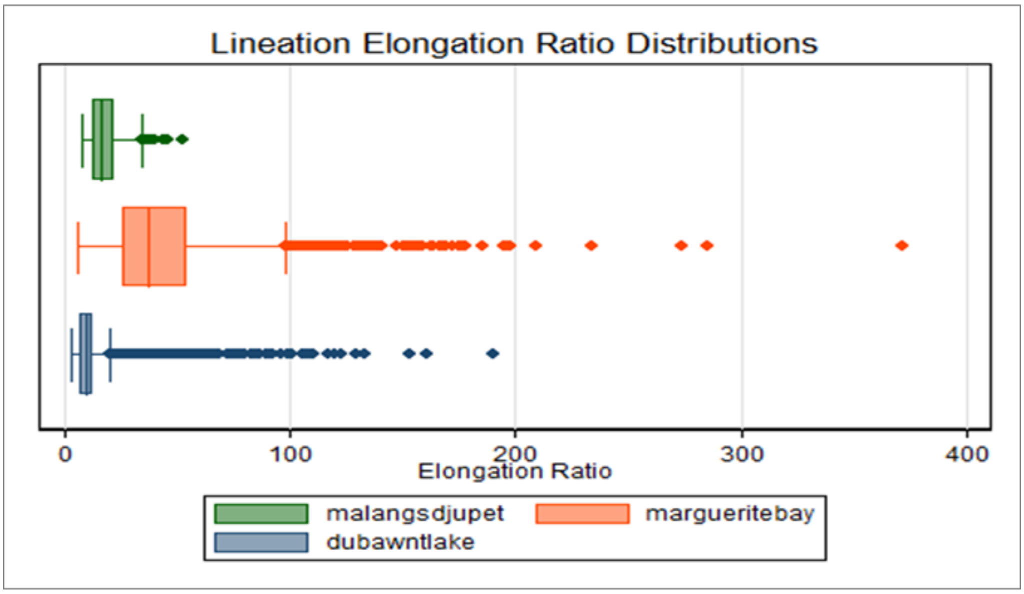

Figure 4.26: *Box plots comparing the lineation elongation ratio distributions for the three palaeo-ice stream beds mapped. The boxes enclose the 25th to the 75th percentile, with the median represented by the central line, while the whiskers represent the 5th and 95th percentiles.*

Table 4.3: *Summary statistics on lineation elongation ratio from all three palaeo-ice streams.*

	Dubawnt Lake	Marguerite Bay	Malangsdjupet
Number of Lineations	17,110	2,065	307
Minimum	4	6	8
25th Percentile	7	26	13
Median	9	37	17
Mean	11	46	18
75th Percentile	12	55	22
Maximum	190	372	52
Inter Quartile Range	5	29	9
Range	186	366	44
Standard Deviation	8	32	8
Skewness	6.2	2.5	1.4
Kurtosis	69.9	11.5	2.1

The median elongation ratio of the lineations from the Marguerite Bay (37.1:1) (Figures 4.25 and 4.26) palaeo-ice stream is considerably greater than that for either of the other palaeo-ice stream beds, 9.3:1 (Dubawnt Lake) and 16.6:1 (Malangsdjupet). Similarly the IQR for the Marguerite Bay population (28.9:1) is much greater than for either Dubawnt Lake or Malangsdjupet (5:1 and 8.6:1

respectively). The Dubawnt Lake population does, however, display a considerable number of lineations with relatively high elongation ratios, up to190:1, whereas the highest elongation ratio for Malangsdjupet is 52.2:1.

The skewness and kurtosis values, which describe the shape of a distribution relative to that of the normal distribution, presented in each of the three statistical tables emphasise the fact that all of the distributions are skewed to the right with extreme values at the higher end of the distribution. The prevalence of extreme values means that the mean is likely to be skewed toward higher values. It follows that the median, which is less effected by extreme values, is a more useful average measure to use when comparing the three palaeo-ice streams.

4.4. Testing the groove-ploughing predictions:

In Section 3.4 and 3.5 three measures, designed to test two predictions of the groove-ploughing theory, were described. Each method has been applied to the data from the Marguerite Bay and Malangsdjupet palaeo-ice stream beds while two of the measures, designed to test predictions related to lateral spacing of lineations, have been applied to data from all three palaeo-ice stream beds. In this section results derived from these measures will be presented for each of the three palaeo-ice stream beds studied in turn.

4.4.1. Dubawnt Lake:

4.4.1.1. Lateral Spacing of Lineations:

The predictions of the groove-ploughing theory, as outlined by Clark *et al*. (2003) and discussed in Section 2.4.3, state that lateral spacing of lineations should increase in the downstream direction (Figure 3.5). The measure devised to test this prediction is based on lineation (as described in Section 3.5). Figure 4.27 (below) displays the results of this measure for the Dubawnt Lake lineation population.

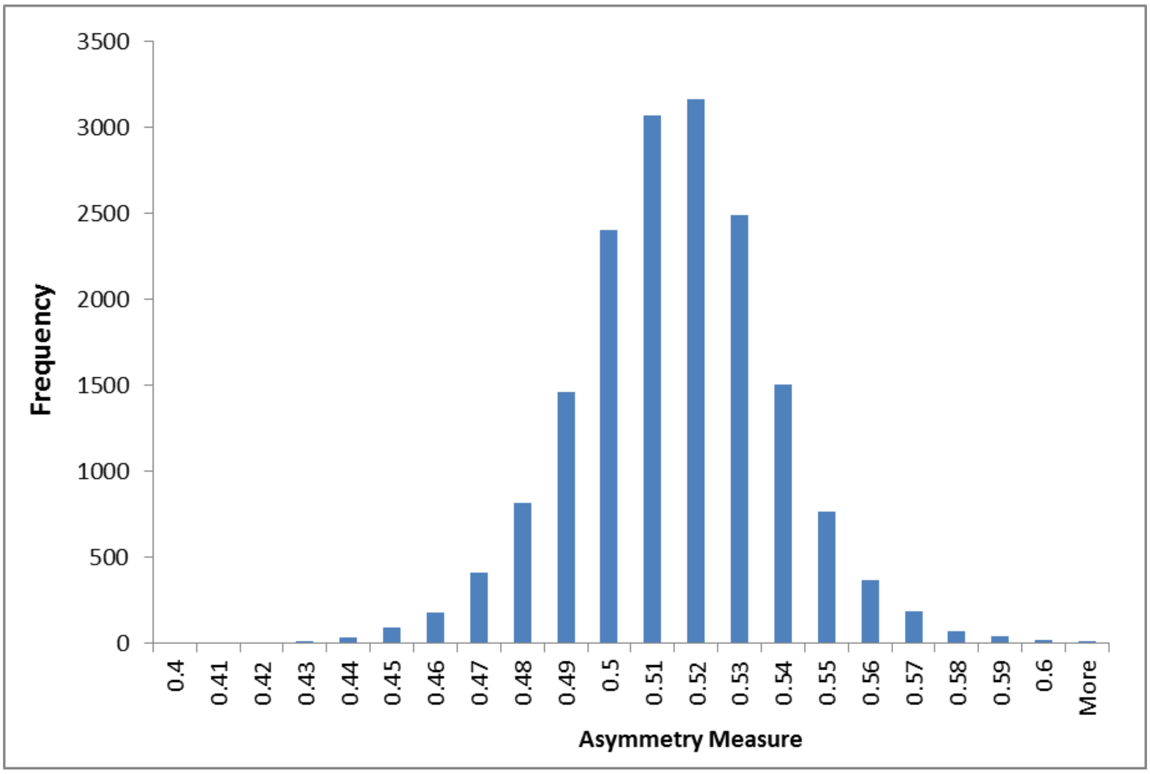

Figure 4.27: *Lineation asymmetry measure using the position of the lineation centre of gravity relative to the lineation endpoints. Note that lineations with values of this measure above 0.5 conform to the groove-ploughing prediction while those with values below 0.5 do not.*

The lineation asymmetry measure, Figure 4.27, peaks in the 0.5-0.52 classes and is relatively symmetrically distributed about this peak. It is notable that a large number of lineations have values of the asymmetry measure below 0.5.

4.4.2. Marguerite Bay:

4.4.2.1. Lateral Spacing of Lineations:

The same measure is used to examine lineation lateral spacing for the Marguerite Bay palaeo-ice stream bed. The results of this measure are presented in Figures 4.28 (below).

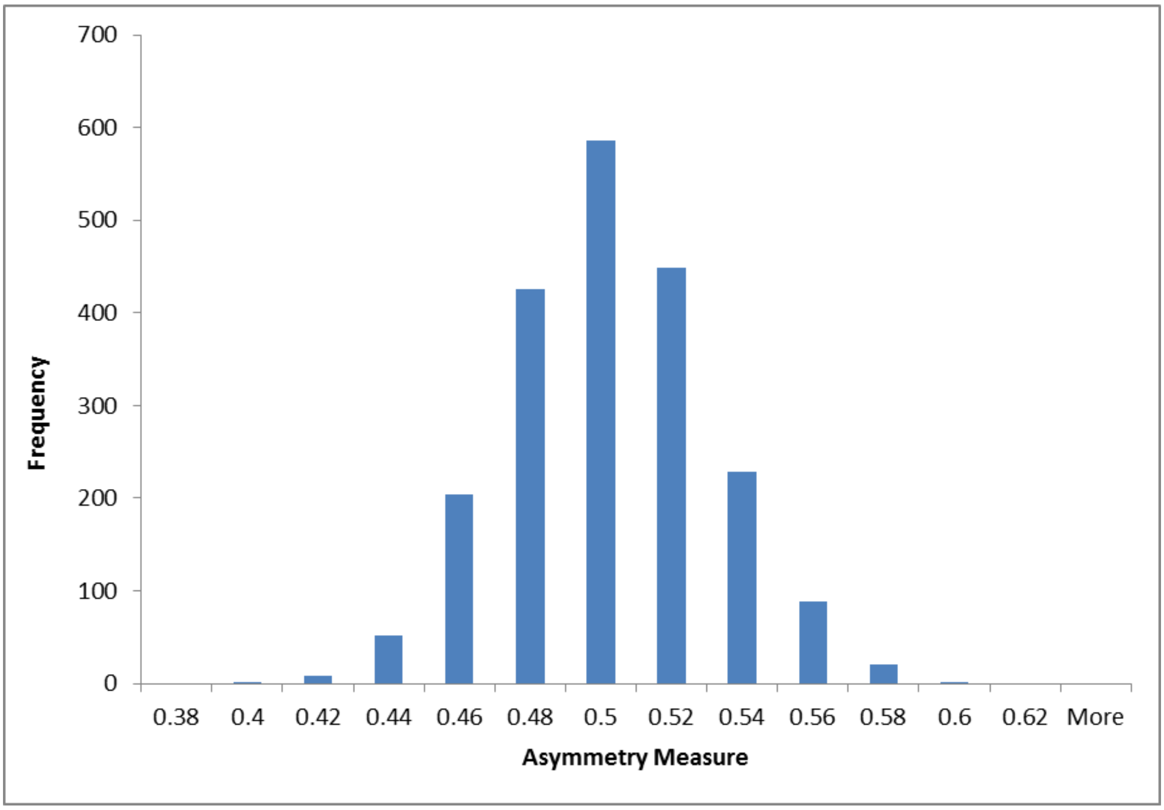

Figure 4.28: *Lineation asymmetry measure using the position of the lineation centre of gravity relative to the lineation endpoints, for the lineations from the Marguerite Bay palaeo-ice stream. Note that lineations with values of this measure above 0.5 conform to the groove-ploughing prediction while those with values below 0.5 do not.*

4.4.2.2. Lineation Amplitude:

The groove-ploughing predictions state that lineation amplitude should decrease in the downstream direction as the keel ploughing the groove progressively melts out (see Section 2.4.3). In order to test this prediction two methods, using either transects along the lineations or transects perpendicular to a group of lineations, were devised (see Section 3.6). The arrangement of the transects, taken approximately perpendicular to the direction of lineation orientation, is shown in Figure 4.29 (below).

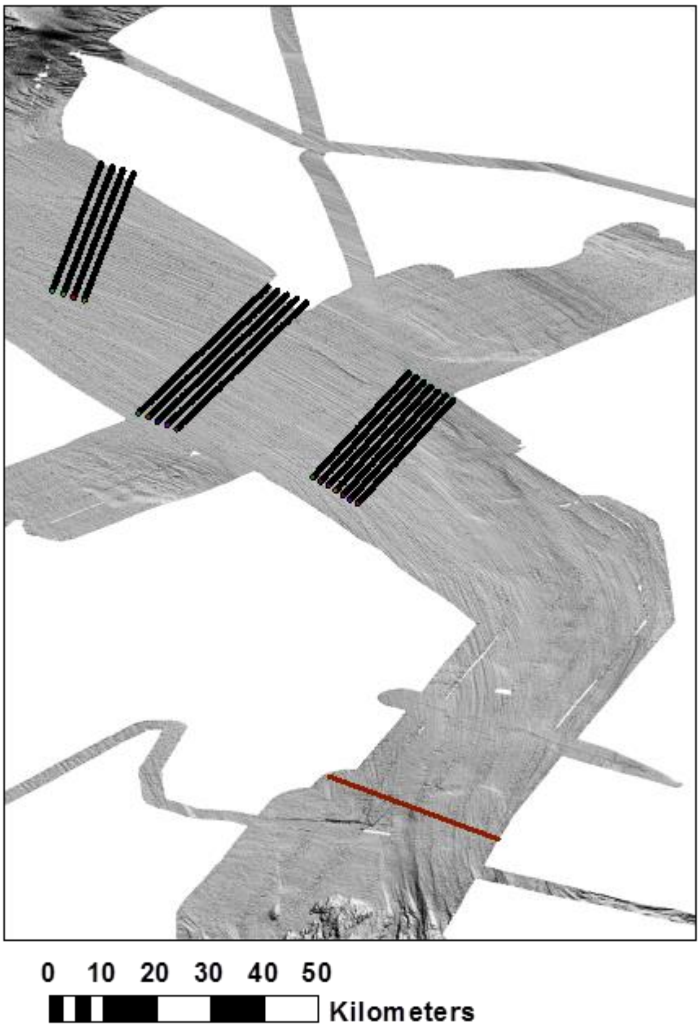

Figure 4.29: *Hillshade image of the outer area of the Marguerite Bay palaeo-ice stream derived from swath bathymetry. The red line represents the upstream limit of lineation mapping chosen in this study, while the remaining lines (and points) are the locations of the profiles extracted to examine downstream change in lineation elevation.*

Three groups of transects (each individual line 1 km apart from the next) were taken at points along the Marguerite bay palaeo-ice stream (as shown in Figure 4.29). The reason for having different numbers of transects in each of the groups of transects (shown in Figure 4.29) is that there is a trade-off between distance covered (i.e. number of transects) and the number of lineations covered. The results from the upstream group of transects is shown in Figure 4.30 and the results from the two downstream groups of transects is shown in Figure 4.31 (with only the values for lineations that cross all of the transects in each group displayed).

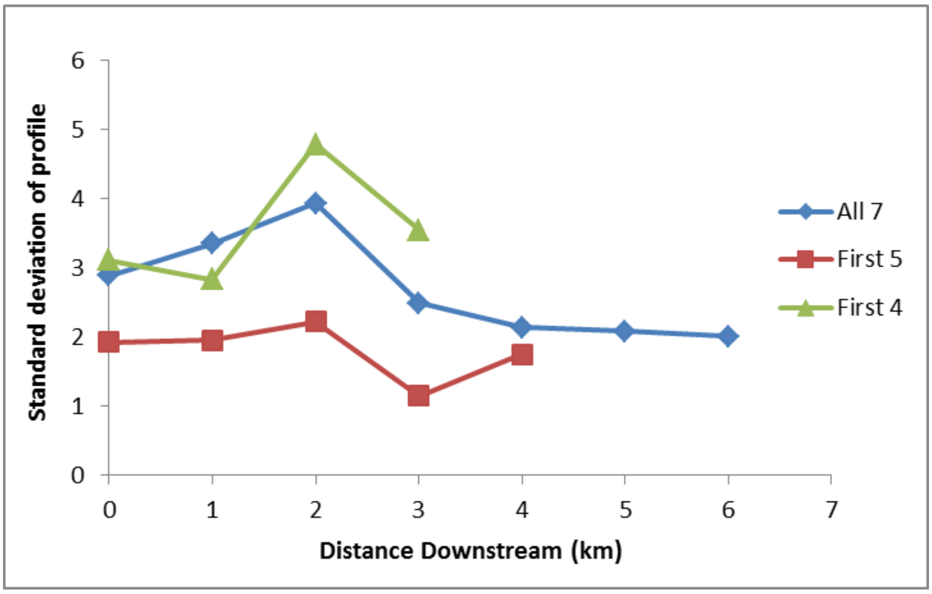

Figure 4.30: *Line graph showing the downstream change in standard deviation of elevation profile data for groups of lineations. Each point represents the standard deviation of detrended elevation data extracted from one of the profiles in Figure 4.32. The three different lines represent groups of lineations that cross a given number of profiles.*

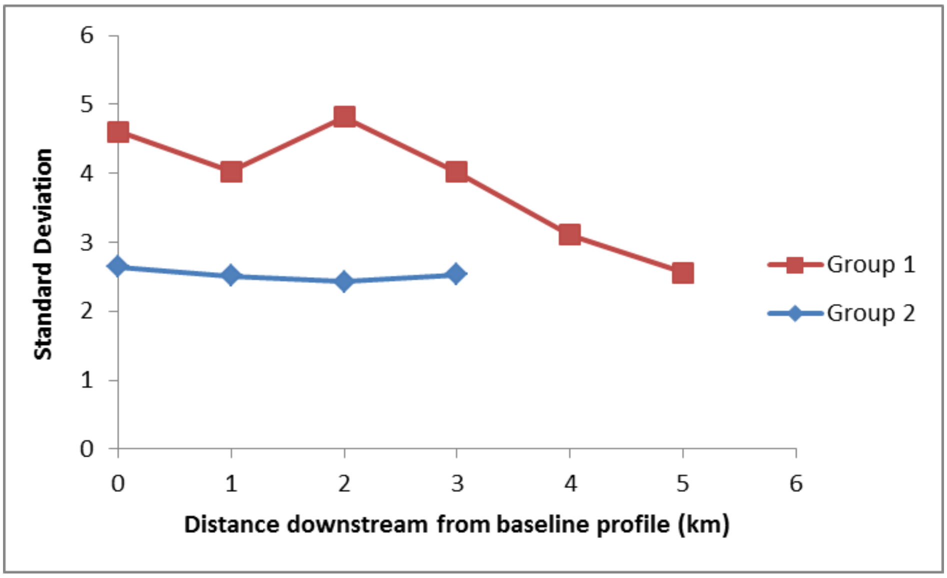

Figure 4.31: *Line graph showing the downstream change in standard deviation of elevation profile data for groups of lineations. Each point represents the standard deviation of detrended elevation data extracted from one of the profiles in Figure 4.32. The two lines represent the lineation amplitude values for lineations crossing all of the lines in two of the groups of transects seen in Figure 4.29.*

The second method used to analyse downstream change in lineation amplitude is the 'Along Crest' measure described in Section 3.6.2. Due to the fact that this technique is only semi-automated, a sample of 50 lineations was selected from across the palaeo-ice stream bed. The results from this measure are shown in Figure 4.32.

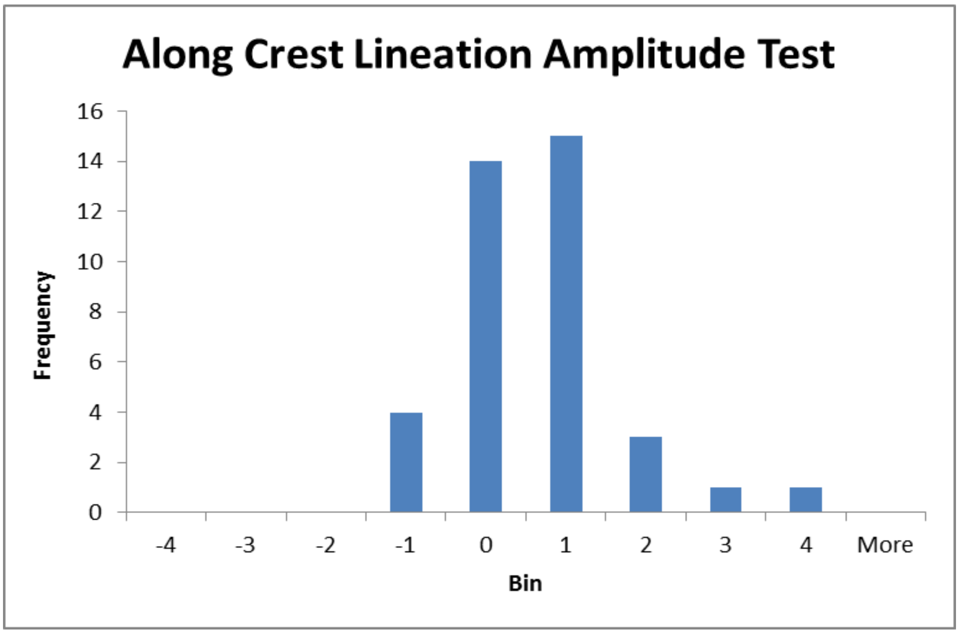

Figure 4.32: *Histogram showing the difference in average elevation values between the upstream and downstream halves of a sample (n=50) of lineations from the bed of the Marguerite Bay palaeo-ice stream. A positive result indicates that a lineation's upstream half has greater along crest elevation than the same lineation's downstream halve. A positive value of this measure is therefore a confirmation of the prediction of the groove-ploughing theory whereas a negative result is not.*

The lineation asymmetry measure peaks at 0.5 and is again close to symmetrical about this modal class. This would suggest that there is no particular tendency toward lineation asymmetry and hence the lineations do not conform to the lateral spacing prediction of the groove-ploughing theory. The NNP based measure, however, has peaks at both ends of the expected 0-1 range with considerable numbers of lineations also exceeding a value of 1 (which should be impossible with this measure).

The transect measure, in general, shows slight decreases in lineation amplitude downstream although there are examples, e.g. the notable peak seen in the

Figure 4.30 amplitude values at 2 km downstream, of downstream amplitude increases within a general pattern of downstream amplitude decrease. Similarly the ‘lineation crest’ method has a peak in the 0-2 m range with relatively few lineations with values below 0. This suggests that the majority of lineations display slight downstream decreases in amplitude, although many of these values lie within the range of error of the elevation data.

4.4.3. Malangsdjupet:

4.4.3.1. Lateral Spacing of Lineations:

The same measure was used to examine lineation lateral spacing for the Malangsdjupet palaeo-ice stream bed. The result of this measure is presented in Figures 4.33 (below).

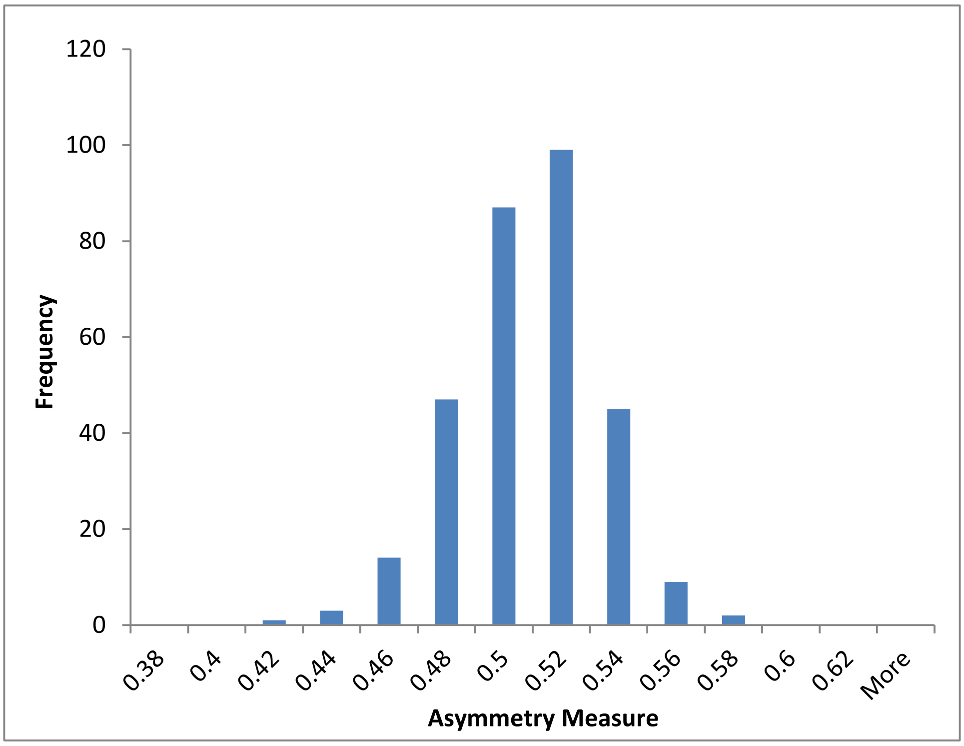

Figure 4.33: *Lineation asymmetry measure using the position of the lineation centre of gravity relative to the lineation endpoints. Note that lineations with values of this measure above 0.5 conform to the groove-ploughing prediction while those with values below 0.5 do not.*

The lineation asymmetry measure results, Figure 4.33, again show a close to symmetrical distribution about a modal group of 0.52-0.54 with all lineations having values in the range 0.4-0.6. This is a similar result to that observed for the Dubawnt Lake and Marguerite Bay palaeo-ice streams.

4.4.3.2. Lineation Amplitude

Two sets of profiles, shown in Figure 4.34, were used to examine downstream change in lineation amplitude. The positions of these two sets of profiles were chosen in order to examine the amplitude change for lineations near the head of the trough, as well as those near the shelf break. Compared to the transects used for the Marguerite Bay palaeo-ice stream bed, those used for Malangsdjupet cover a significantly smaller number of lineations due to the narrower trough. The results from these transects are shown in Figures 4.35 and Figure 4.36.

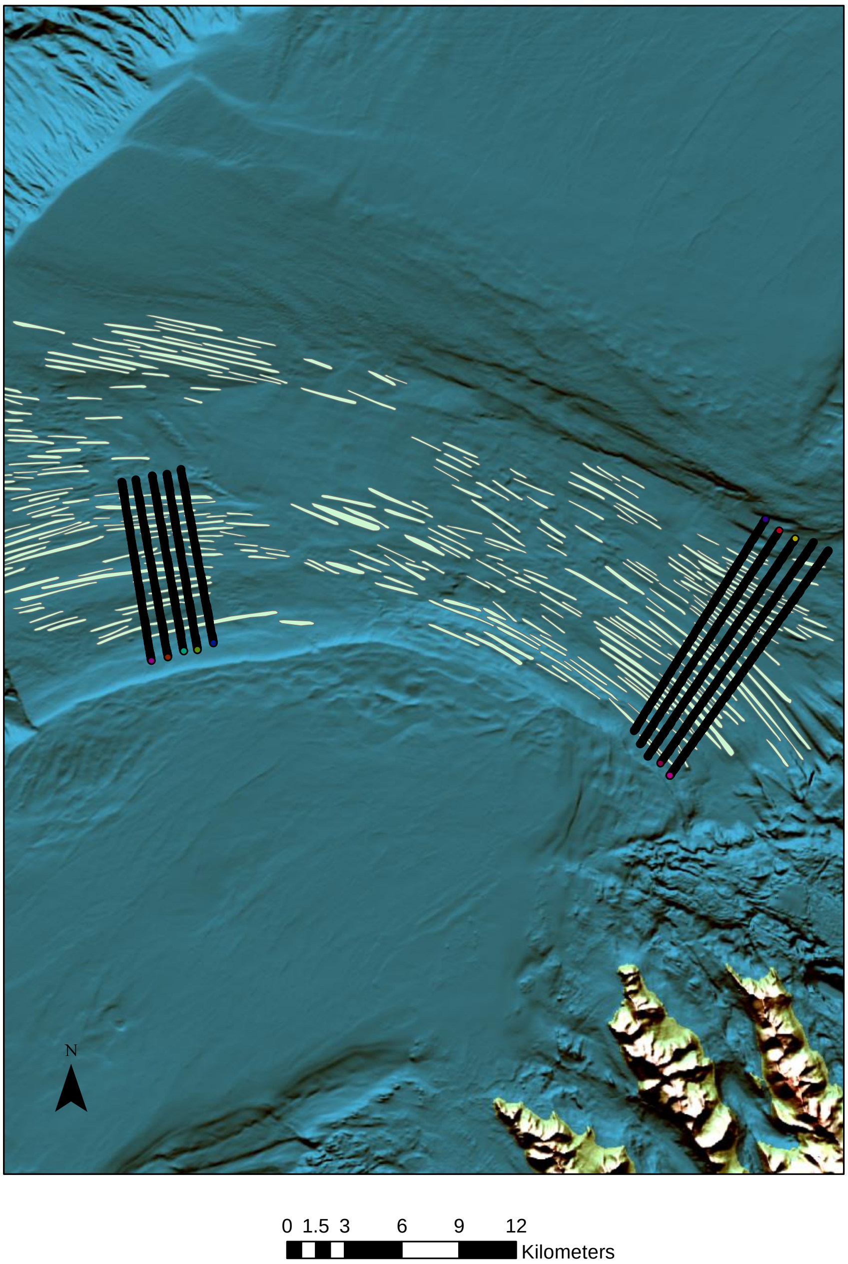

Figure 4.34: *Shaded relief image of the Malangsdjupet trough showing the digitised lineations and the position of the profile lines from which elevation data has been extracted.*

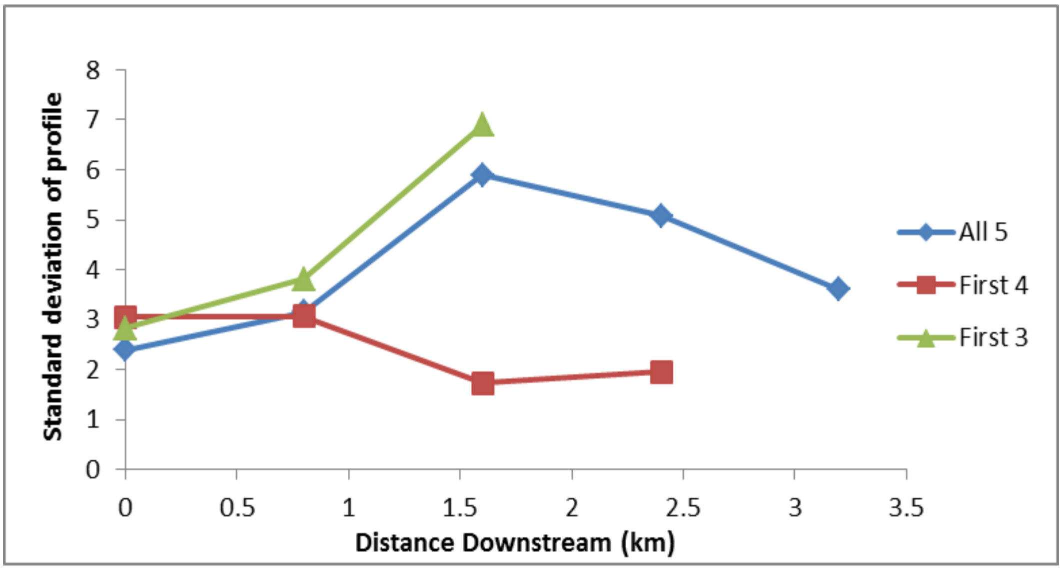

Figure 4.35: *Line graph showing the downstream change in standard deviation of elevation profile data for groups of lineations. Each point represents the standard deviation of detrended elevation data extracted from one of the profiles in Figure 4.37. The three different lines represent groups of lineations that cross a given number of profiles.*

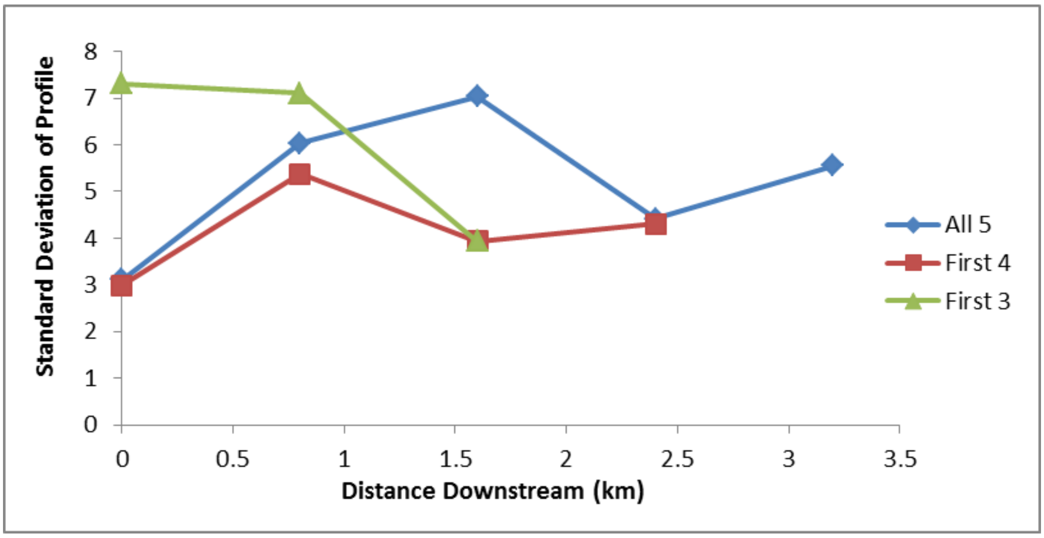

Figure 4.36: *Line graph showing the downstream change in standard deviation of elevation profile data for groups of lineations. Each point represents the standard deviation of detrended elevation data extracted from one of the profiles in Figure 4.37. The three different lines represent groups of lineations that cross a given number of profiles.*

The measure derived from the two groups of transects, Figures 4.35 and 4.36, show little coherent trend in lineation elevation change downstream. The upstream of the two groups of transects, shown in Figure 4.35, has a peak in transect roughness (the standard deviation for the elevation data extracted along a transect) at 1.5 km downstream of the first (base) transect with two of the three groups of lineations, the blue and green lines in Figure 4.35, showing significant increase in lineation elevation over the distance covered by the transects. The third group of lineations crossed by these transects, the red line in Figure 4.35, shows a slight decrease in lineation elevation in the downstream direction. The second (downstream) group of transects, Figure 4.36, show a slight increase in lineation amplitude downstream for two of the three groups of lineations crossing these transects.

A sample of 50 lineations, selected from across the palaeo-ice stream bed, was taken in order to use the ‘Along Crest’ measure of lineation amplitude change. The results of this measure are shown in Figure 4.37.

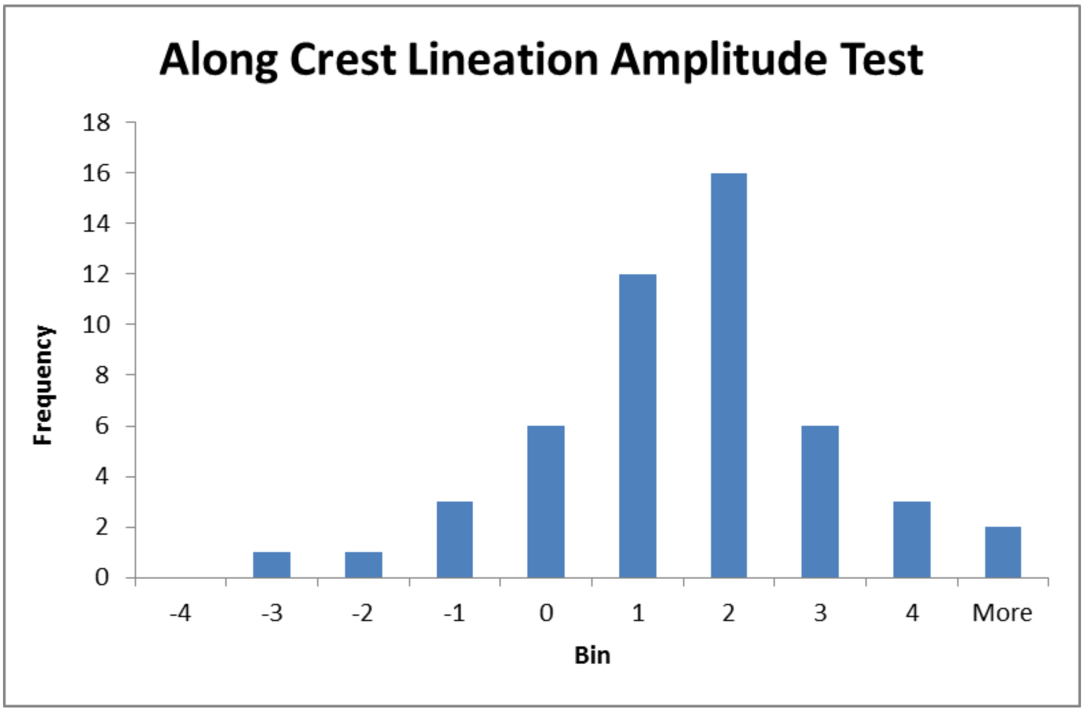

Figure 4.37: *Histogram showing the difference in average elevation values between the upstream and downstream halves of a sample of lineations (n=50) from the bed of the Marguerite Bay palaeo-ice stream. A positive result indicates that a lineation’s upstream half has greater along crest elevation than the same lineation’s downstream half. A positive value of this measure is therefore a confirmation of the prediction of the groove-ploughing theory whereas a negative result is not.*

The results of the along crest amplitude test, Figure 4.37, display a peak in the 1-2 m group with relatively few lineations having values below 0. These two measures, therefore, seem to produce contrary results and hence will give different conclusions regarding the predictions of the groove-ploughing theory.

4.6. Summary:

The results of the analysis of lineation morphology, presented in this chapter, show that all morphological variables have positively skewed distributions that overlap with one another. In terms of lineation length and elongation ratio, Marguerite Bay and Malangsdjupet have higher means than Dubawnt Lake. Both Marguerite Bay and Dubawnt Lake, however, have a relatively small number of lineations of extreme length and elongation ratio values. The lineation width distributions are very similar for all three palaeo-ice stream beds, with the Dubawnt Lake and Marguerite Bay distributions having nearly identical shapes.

The test of lineation asymmetry finds that all three lineation populations are unimodally distributed around a value of approximately 0.5 (i.e. complete symmetry). Both measures designed to test change in lineation amplitude show that while a relatively large portion of the lineation populations studied do decrease in amplitude downstream (as predicted by the groove-ploughing theory) a significant proportion do not. The technique that uses perpendicular transects finds that there is considerable downstream variation in lineation amplitude. In general, while many lineations do indeed decrease in amplitude downstream it is clear that this is not a universal observation.

5. Discussion

5.1. Introduction:

The previous chapter presented analysis of the morphology of the three lineation populations and the results of other measures, designed to test the predictions of the groove-ploughing theory. Relating these results to the body of literature relating to MSGLs and the theories regarding their formation is the purpose of this chapter. In particular, comparing the morphology of the lineations in this study to the morphology of MSGLs, and drumlins, described in the literature will form the first section of this chapter. This will allow examination of how lineation morphology differs between palaeo-ice stream beds and how the values compare to those from the literature (compiled in Tables 1, 2 and 3).

The second part of this chapter will look at the results of the measures designed to test the groove-ploughing theory. This will attempt to review the likelihood of lineation formation by groove-ploughing having occurred for any of the three palaeo-ice streams studied. A key issue to address in this discussion is the suitability of the four primary measures used in this work to test the predictions of the groove-ploughing theory.

5.2. Morphology of MSGL populations:

Mapping of lineations from the three palaeo-ice streams show morphological values broadly fitting with the Clark (1993) quantitative description of MSGLs. Median length values (0.73 km, 2.82 km and 2.09 km), however, tend to be shorter than many of those reported in the literature (Table 2.1). All three palaeo-ice stream beds have positively skewed and long tailed length distributions with lineations of extreme length (up to 41 km for Marguerite Bay), and elongation ratio (ER), within areas of generally shorter, less elongate lineations (many of which might be better described as drumlins). It is possible that this is a common feature of MSGL flowsets and that reporting of morphological values in the literature tends to focus on maximum values.

All three lineation populations have similar lineation width distributions, with those of Marguerite Bay and Dubawnt Lake being extremely similar (median of

~80 m and the majority lineations within the range 40-200m). These values broadly fit with those reported in the literature (Table 2.2), although lineations with much greater widths have been suggested to be MSGLs, e.g. lineations with widths of 1-5 km in the Barents Sea reported by Winsborrow *et al*. (2010). Lineation width and length are relatively poorly positively correlated for all three beds (r^2= 0.19-0.24).

The similarity in lineation width distributions and the relatively poor correlations between lineation length and width perhaps suggests a common method of bedform streamlining. That bedforms may initiate as stubby forms which become more elongate under ice moulding has been previously been suggested (e.g. Clark, 1993 and Clark *et al*., 2009). This is supported by the length dependent ER limit found by Stokes et al., *in prep* for the Dubawnt Lake dataset used in this work and the generally poor correlations between lineation length and width for the Marguerite Bay and Malangsdjupet lineation populations.

The shapes of the three lineation ER distributions are quite different from one another and quite similar to their length distributions. This is presumably partially due to the similarity of the width distributions and the fact that lineation length has a stronger influence on ER than lineation width. The Marguerite Bay lineation population has the highest median ER (37:1) and by far the least peaky distribution, while Dubawnt Lake has a relatively low median (9:1) and a very peaky distribution. This may be because the Dubawnt Lake lineation population has several areas, particularly near the edges of the flowset, where most lineations are of low ER and are perhaps best described as drumlins.

Both the Marguerite Bay and Dubawnt Lake lineation populations have a small number of lineations with extreme ERs (maximums of 372:1 and 190:1 respectively). These ratios are higher than any values explicitly reported in the literature (the highest noted in the literature is 105:1 (Andreassen *et al*., 2004)). Although these lineations with extreme ERs are amongst the longest from their respective populations it would seem that relatively low width values for lineations of this length is the primary reason for the extreme ER values. Indeed, lineation populations with much greater maximum lengths and considerably lower maximum elongation ratios are reported in the literature (e.g.

Andreassen *et al*., 2008). The Malangsdjupet lineation population, however, has a maximum ER value of 52:1 reflecting the greater lineation widths found for this palaeo-ice stream bed.

While all three populations have distinct length and elongation ratio distributions all of three distributions overlap to a significantly extent. When considered alongside the relatively wide range of morphological values reported from other flowsets in the literature this suggests that MSGL morphology differs widely between different palaeo-ice stream beds. Whether this indicates different formation mechanisms or merely different glaciological parameters for the palaeo-ice streams is not clear. .

As already noted, the Malangsdjupet lineation population displays generally wider lineations and has no lineations with extreme ER values. It also has a similar strength correlation between lineation length and width values (r^2= 0.24) as the other two palaeo-ice streams. This may perhaps suggest that the Malangsdjupet population has not undergone the same level of remoulding. Another possibility, however, is that further lengthening, and streamlining, was prevented by the presence of a bathymetric high in the mid-trough, which is not overprinted by lineations.

5.3. Comparison with drumlin morphology:

Comparison of the lineations, from this study, with the data for UK drumlins presented by Clark *et al.* (2009) shows that a considerable overlap is seen with the Dubawnt Lake lineation length distributions, and to a lesser extent with the Marguerite Bay and Malangsdjupet length distributions (Figure 5.1). Interestingly, lineation width values for the British drumlin sample are generally greater than those found for any of the three palaeo-ice streams in this study. This may be explained by the suggestion, from Stokes *et al.* in prep, that MSGLs may lengthen at the expense of their width as material is eroded from the sides of the lineation and redeposited near the end of the lineation. In order to properly examine this hypothesis an analysis of lineation volume would be necessary.

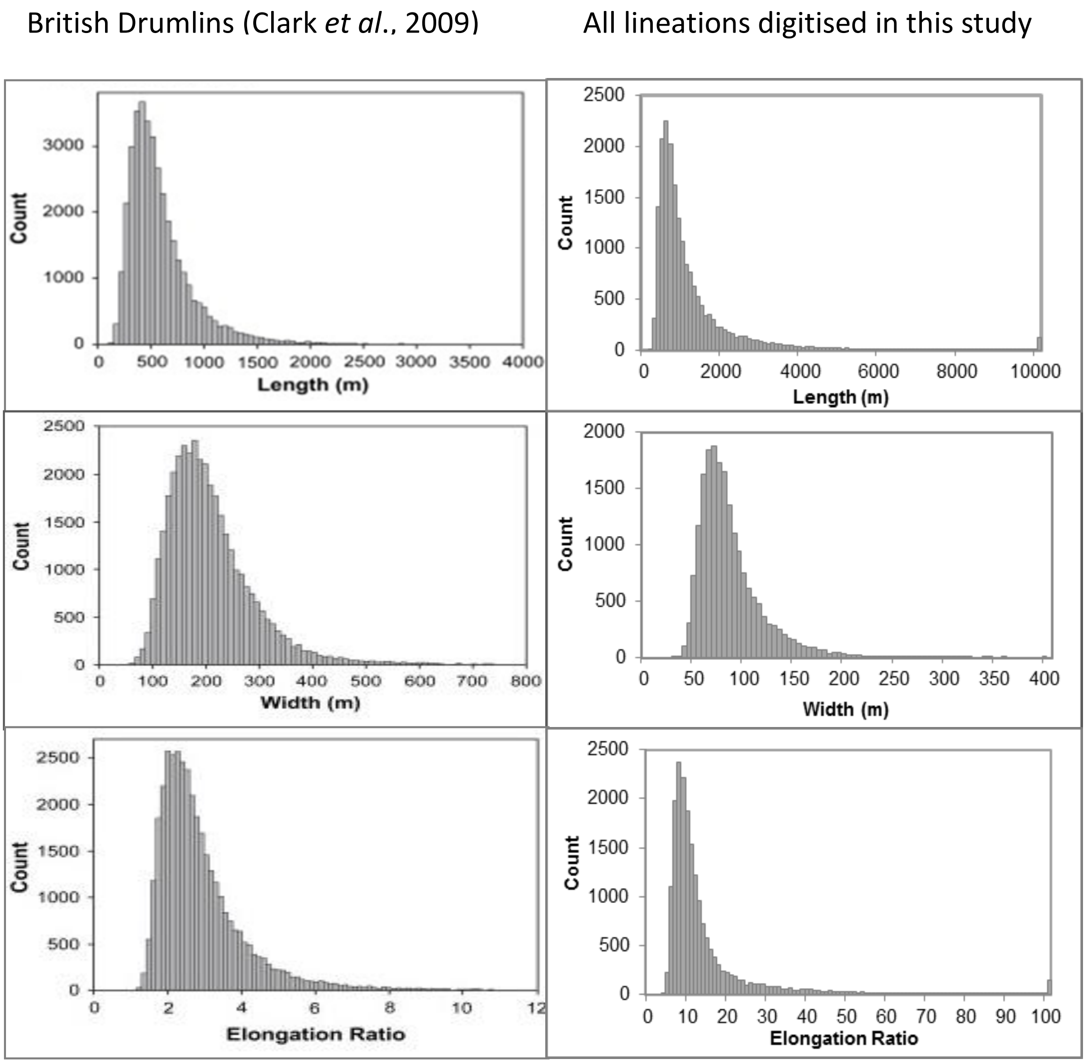

Figure 5.1: *Comparison of the morphology of all of the MSGLs digitised in this project and the British drumlin population studied by Clark et al (2009) (the histograms on the left-hand side). For the British drumlins n= 37,043, whereas for the lineation data from this study n= 19,482.*

The morphology of the three lineation populations, and the UK drumlin sample (Clark *et al*., 2009), seem to be compatible with the idea, suggested by various authors (e.g. Rose, 1987), of a subglacial bedform continuum. This idea suggests that subglacial bedform categories (e.g. ribbed moraine, drumlins and MSGLs) are genetically related to one another and that no entirely separate lineation populations can be isolated. It is also interesting that the lineations digitised in this work are generally less wide than the UK drumlin sample, this may suggest that significant streamlining occurs and could adequately explain the morphological differences between drumlins and MSGLs.

5.4. Comparison of groove-ploughing test measures:

The three techniques developed to test the groove-ploughing theory examine two of the theories predictions, as outlined by Clark *et al.* (2003). Since two separate methods have been developed for examining lineation amplitude it should be possible to compare the results of these measures to examine the comparability, and to some extent reliability, of these measures. It must be noted, however, the ‘lineation transect’ technique (see Section 3.5.1) is testing only for the parts of lineations crossed by the transects rather than for the entire lineation length, as for the ‘lineation crest’ technique (see Section 3.5.2), and so comparisons between them are difficult.

Both measures of that examine lineation amplitude generally show amplitude decreasing, or remaining approximately constant, in the downstream direction for most lineations examined. The transect method, however, shows some considerable variations in amplitude, in many cases possibly due to error in the elevation data, along the length of the lineations examined. These variations in amplitude are probably averaged out by the lineation crest method, but it is difficult to be certain of this. The primary limitation on the measurement of lineation amplitude seems to be the error attached to the DEMs used in the calculations.

It should also be possible to compare the results of the tests of the two predictions, in order to see if there are significant numbers of lineations that conform to both of the groove-ploughing predictions. If a large subset of the lineations does conform to the predictions of the groove-ploughing theory, they could be interpreted as allowing for the possibility of a limited phase of groove-ploughing having occurred during or after the formation of the bulk of the MSGL population.

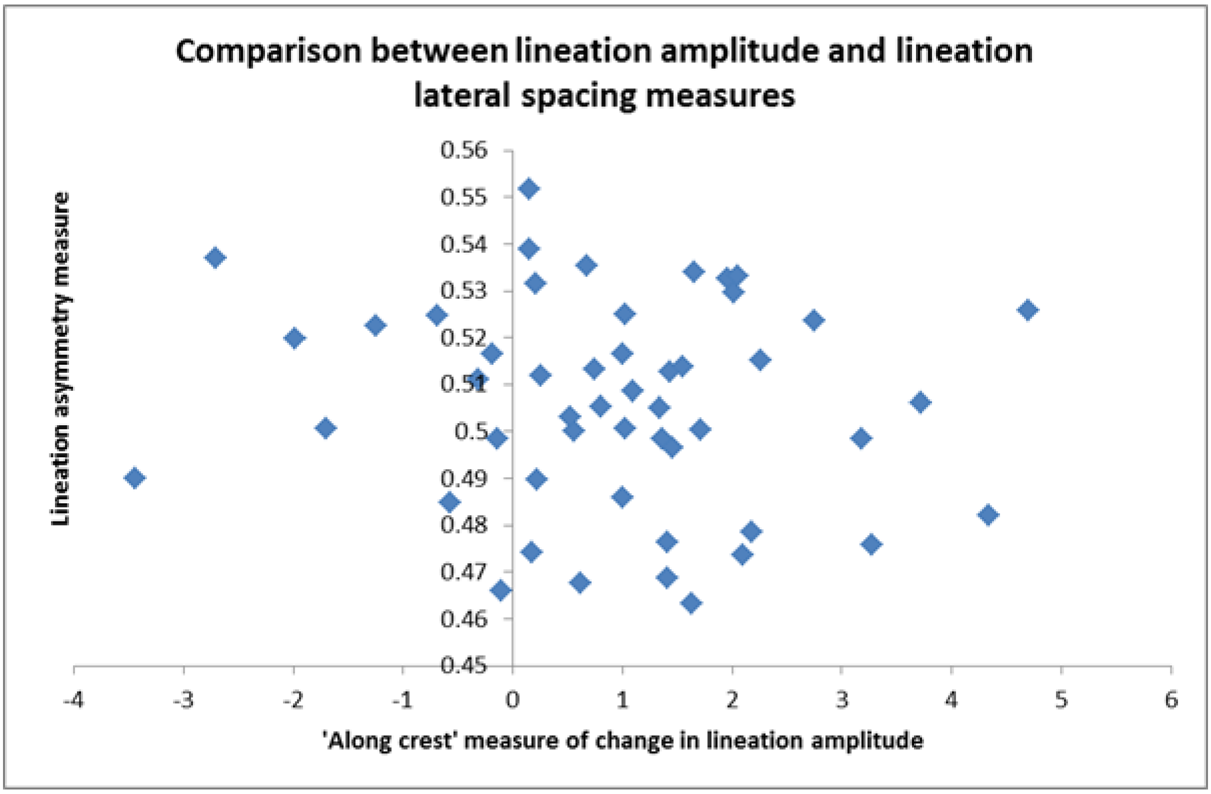

Figure 5.2: *Comparison of measures designed to test lineation lateral spacing and lineation amplitude (n= 50).If individual lineations conform to the morphological predictions of the groove-ploughing theory then they should have a lineation amplitude measure value above 0 and a lineation asymmetry measure value above 0.5.*

It is also possible to examine whether individual lineations conform to both of the groove-ploughing predictions being tested, i.e. does lineation lateral spacing increase and lineation amplitude decrease in the downstream direction. This was done by comparing the lineation asymmetry and lineation crest techniques for a sample 50 lineations from the Malangsdjupet palaeo-ice stream bed, as shown in Figure 5.2. The results of this comparison show that many lineations, from the Malangsdjupet palaeo-ice stream do indeed conform to both predictions although no direct relationship between the variables is apparent. The relatively low range of values of the asymmetry measure (i.e. around 0.5) makes such a comparison difficult. It is possible to suggest, that this result allows for the possibility that some of the lineations studied could have formed as the result of a secondary phase of groove-ploughing (perhaps acting as a subsidiary to another lineation formation process), although the sample of lineations tested is relatively quite small.

5.5. Are the results derived from these measures compatible with a groove-ploughing origin?

Testing the groove-ploughing theory requires comparison of morphology of lineation populations with the predictions of Clark *et al*. (2003). In the previous section (Section 5.3) the methods specifically devised to quantitatively test the prediction regarding downstream change in amplitude and transverse spacing of lineations, prediction 5 in the list of Clark *et al*. (2003), were reviewed. A number of other predictions and observations, such as the apparent lineation bifurcation discussed by Ó Cofaigh *et al*. (2005), may also provide the subject for qualitative discussion of the applicability of the groove-ploughing theory using observations presented in this study and the existing literature. In this section, the evidence for and against lineation formation by groove-ploughing will be considered for each palaeo-ice stream bed studied.

5.5.1. Dubawnt Lake:

The lineation asymmetry method shows that the majority of lineations are very near symmetrical and hence show little significant tapering at their downstream ends. The values of the asymmetry measure are also approximately symmetrically distributed about the 0.5 value, which in theory represents an entirely symmetrical bedform, showing that there is no significant group of lineations with tapered downstream ends. This is in agreement with the results of Spagnolo *et al*. (2010) and Stokes *et al*., in prep. that both use a similar measure to examine asymmetry of the Dubawnt Lake lineations.

No obvious examples of lineations displaying bifurcation or merging were noted during the digitising of the lineations. Furthermore, no examples of the bedrock obstacles that could have created the ice keels necessary for groove-ploughing were noted during mapping. Stokes *et al*. *in prep*, however, note a relatively thin till cover (several metres thick at most) which means that bedrock roughness could indeed potentially influence the shape of the ice base. Creation of ice keels by convergence of flow (suggested by Clark *et al*., 2003) is also possible given that most of the extremely elongate bedforms occur in the narrowest part of the flowset.

A further prediction of the groove-ploughing theory is that groove spacing should be greatest in the zone of convergence rather than in the narrower trunk of the flowset. The analysis of bedform density, per area of the flowset, by Stokes *et al*. (2003) (using a polyline dataset) and Stokes *et al*., *in prep* (using the polygon dataset also used in this work) shows that there is no clear pattern of lineation density with areas of high bedform density in both the onset zone and the trunk zone. Unfortunately no analysis of lineation amplitude was possible for the Dubawnt Lake flowset because of the lack of DEMs of the area with suitable resolution and accuracy.

5.5.2. Marguerite Bay:

The lineation asymmetry measure again suggests that the majority of lineations are approximately symmetrical and hence do not conform to the predictions of the groove-ploughing theory. Downstream change in lineation amplitude was examined using the transect technique, with three separate groups of 4-7 transects each, and the along lineation crest technique, using a sample of 50 lineations. The transect technique showed a general decrease in lineation amplitude in the downstream direction, despite some variability. Similarly, the lineation crest technique showed that most lineations decreased in mean amplitude downstream although many of the recorded values were within the range of error for the elevation data. The results from these two measures, of lineation amplitude, seem to broadly support the predictions of the groove-ploughing theory.

A small number of the lineations in the area upstream of those mapped displayed what appeared to be large boulders, or other large obstacles, at their stoss ends (Figure 4.8). These lineations generally appeared to taper downstream and were not mapped because they were less elongate then bedforms further downstream and appeared to be in an area with a much less dense arrangement of bedforms. These landforms are perhaps overly long to be crag-and-tails, formed by a pressure shadow in the lee of the obstacle, and perhaps provide some support for limited groove-ploughing. A similar observation was noted by Ó Cofaigh *et al*. (2005), but the vast majority of lineations had no observable upstream obstacle.

The suggestion of lineation bifurcation and merging made by Ó Cofaigh *et al*. (2005) has proved hard to confirm. In several places on the palaeo-ice stream bed, groups of lineation appeared to reduce in number as they were mapped downstream. The subtlety of the apparent merging, however, prevented them being mapped with any certainty and, when digitising lineations, possible examples of merging were ignored in favour of terminating one of the two lineations. Clearer examples of cross cutting of lineations were evident near the edge of the shelf, where a small set of lineations with a different direction overprinted other lineations. The fact that the apparent lineation merging, and bifurcation, could not be separated from possible subtle cross cuts, and initiation of new lineations within grooves, means that these observations do not pose a major objection to the groove-ploughing theory.

5.5.3. Malangsdjupet:

The lineation asymmetry measure once again gives an approximately symmetrical distribution, about a modal group of 0.52-0.54, which suggests that the majority of lineations do not display the significantly increased downstream lateral spacing predicted by the groove-ploughing theory. A few lineations at the upstream end of the flowset seem to display a relationship with bedrock obstacles at their stoss end. The majority of lineations in the flowset, however, do not have obvious bedrock obstacles at their upstream ends. Similarly a few possible cases of lineations merging downstream were observed but it is not possible to be entirely sure that these are genuine examples of lineation merging rather than local cross cutting.

5.6. General applicability of the groove-ploughing theory:

The lineation asymmetry measure has for all three palaeo-ice stream beds in this study shown that there is no particular tendency towards asymmetry in either sense. This result seems to indicate that the downstream increase in lateral spacing, for each lineation, predicted by the groove-ploughing theory is not observed for any of the three lineation populations mapped in this work. This lack of lineation asymmetry tallies with the results of Spagnolo *et al*. (2010) (for drumlins) and Stokes *et al.*, in prep (for the Dubawnt Lake lineation population) which both use a similar measure.

Both measures of lineation amplitude generally show amplitude decreasing, or remaining approximately constant, in the downstream direction for most lineations examined. Although both lineation amplitude measures generally seem to show support for the groove-ploughing theory the transect method does show some examples of increasing lineation amplitude in the downstream direction. As already noted however, the relatively high vertical errors (between 1 and 5 m) of the bathymetric (echo-sounder) data are of a similar magnitude to many of the amplitude changes measured.

There have been relatively few observations of obstacles upstream of lineations that could have caused formation of ice keels. Although it is possible that some obstacles were buried by sediment following lineation formation, and hence would not be observed, the theory suggests that each lineation should have a bedrock outcrop, or obstacle, at its stoss end. It is possible, however, that flowline convergence could provide the necessary ice base roughness to allow groove-ploughing to operate (Clark *et al*., 2003).

5.7. Other possible formation theories:

Although the primary focus of this work is to test the groove-ploughing theory, this section will briefly examine other proposed MSGL formation theories. The collection of a large sample of data on lineation morphology perhaps presents a possibility to evaluate these theories more thoroughly than has previously been possible. Although various different lineation formation theories exist discussion in this section will be limited to the principle theories discussed in Section 2.4.

5.7.1. Catastrophic Meltwater Floods:

As noted by Ó Cofaigh *et al*. (2005) and Shaw *et al*. (2008) there is landform evidence for meltwater action on the bed of the Marguerite Bay palaeo-ice stream. This takes the form of gullies and channels upstream of the area of elongate lineations and the channel-like features on the slope at the continental shelf break. These features indicate the action of meltwater but whether they represent the turbulent flows proposed by Shaw *et al*. (2008) or more localised (perhaps deglacial) meltwater action, as suggested by Ó Cofaigh *et al*. (2010), is unclear. Major meltwater features are not apparent on the bed of the Dubawnt Lake and Malangsdjupet palaeo-ice streams. The presence of overdeepenings around the stoss end of lineations has also previously been cited as evidence of turbulent meltwater flow. Again, although a few examples of lineations with apparent overdeepenings were noted, from all three palaeo-ice stream beds, they were far from ubiquitous.

5.7.2. Rilling Instability:

The rilling instability theory proposed by Fowler (2010), as an extension of previous work on bedfrom formation by instabilities in a deforming sediment layer (e.g. Hindmarsh, 1998 and Schoof, 2007), showed theoretically that MSGLs could, potentially, be formed by sediment deformation. The theoretical analysis of Fowler (2010) went as far as to use estimates of the values of various parameters to predict a preferred spacing, length and elevation for MSGLs. It is clear that these values depend strongly on the choice of parameters, which are likely be specific to given palaeo-ice stream beds, but they do allow for limited quantitative testing of the theory.

The values predicted by Fowler (2010) are 394 m for lateral spacing, 52.9 km for length and 12.3 m for elevation. The length value is well in excess of the maximum recorded value (41 km) from any of the three palaeo-ice streams studied. The elevation value, however, is at the top end of the range of elevation values observed. The lateral spacing value is somewhat greater than the 233 m calculated by Stokes et al., *in prep* using the Dubawnt Lake data.

While these observations perhaps provide some limited support for the rilling instability theory, it would probably be more useful if the theory were able to predict the shape of the distribution expected for each morphological measure (i.e. lineation length, width and lateral spacing). This work provides some of the morphological data necessary to test any such future development of the theory.

5.8. Further work required to test the groove-ploughing theory

Of the 10 predictions identified by Clark *et al*. (2003) to aid evaluation or falsification of the groove-ploughing theory this work has focused, primarily, on only one (number 5 in the Clark *et al.* (2003) list). This is largely because this prediction was the only one that could be readily tested using the available lineation morphology data. A number of other predictions, related to the relative location of bedrock obstacles could not be examined because these bedrock obstacles, if they existed, were buried. Using acoustic techniques it may be possible to search for these obstacles and hence test these predictions.

Examination of the sediment composition and internal structure of lineations may also prove a very effective method of falsification of bedform formation theories. In particular, the groove-ploughing theory suggests that different lineation morphologies should be produced dependent on whether a till is coarse, or fine, grained. Testing of other formation theories, such as the Mega-flood theory, is also likely to require further evidence regarding the sediment composition of lineations.

A limiting factor in analysis of change in lineation elevation has been the error associated with the bathymetric data used in lineation digitisation. In many cases the vertical error, of between 1 and 5 m, has been larger than the changes in elevation measured using the techniques developed to test the groove-ploughing theory. With the increasing availability of more accurate DEMs, for terrestrial sites, increasingly detailed analysis of change in lineation elevation will probably be possible in the future.

6. Conclusion

6.1. Introduction:

During this project a total of 19,784 lineations were digitised, as polygons, from three different palaeo-ice stream beds. This large sample of lineations has allowed for a thorough examination of the morphology of the lineation populations of a sort that has not previously been possible for MSGLs. Digitising a large number of lineations as polygons has also allowed for testing of the predictions of the groove-ploughing theory.

6.2. Lineation Morphology:

The lineation length and elongation ratio values show that Malangsdjupet and Marguerite Bay (median lineation length values of 2,091 m and 2,816 m respectively) have higher medians than Dubawnt Lake (728 m). Malangsdjupet, however, has no lineations of extreme length and elongation whereas both Malangsdjupet and Marguerite Bay do. Interestingly, the lineation width distributions are extremely similar for all three of the palaeo-ice stream beds (median lineation length values of 75 m, 77 m and 126 m).

All morphological variables have positively skewed distributions that overlap with one another and those produced for UK drumlins by Clark *et al*. (2009) (see Figure 5.1). Another interesting observation is that, on the three beds studied, very long and elongate lineations are often neighboured by much shorter and less elongate lineations, perhaps better termed drumlins. It would seem that the single group of landforms suggested by the term mega-scale glacial lineation, distinct from shorter and less elongate lineations, does not exist (at least on the three palaeo-ice streams examined in this work). This observation would seem to support the suggestion that MSGLs form part of a bedform continuum, with drumlins and perhaps flutes and ribbed moraine, of the sort suggested by various authors (e.g. Rose, 1987).

6.3. The Groove-Ploughing Theory:

The lineation asymmetry measure has, for all three palaeo-ice stream beds in this study, shown that there is no particular tendency towards asymmetry in either sense. This result seems to indicate that the downstream increase in lateral spacing, for each lineation, predicted by the groove-ploughing theory is not observed for any of the three lineation populations mapped in this work.

Both measures of lineation amplitude generally show amplitude decreasing, or remaining approximately constant, in the downstream direction for most lineations examined. Although both lineation amplitude measures generally seem to show support for the groove-ploughing theory, the transect method does show some examples of increasing lineation amplitude in the downstream direction. A notable problem with analysis of lineation amplitude, using either of the methods in this project, is the relatively high vertical errors (between 1 and 5 m) of the bathymetric (echo-sounder) data compared to lineation amplitude generally below 15 m and often considerably smaller.

Other observations that have previously been used to support the groove-ploughing theory, e.g. upstream bedrock obstacles, and the observation of lineation merging and bifurcation, that would not be explicable under the groove-ploughing theory, were also considered. Although in a few cases possible bedrock obstacles were observed, they were not seen for the vast majority of lineations.

In general, the evidence from tests of lateral spacing does not support the groove-ploughing theory and tests of lineation amplitude provide only partial support. Observations of other morphological features also provide little support for the theory. It would seem that this theory does not provide a general mechanism for the formation of the lineations from the three palaeo-ice stream beds studied. Limited episodes of groove-ploughing that form, or modify lineations (perhaps operating in conjunction with an instability mechanism), cannot, however, be ruled out.

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