Relationship between mega-scale glacial lineations and iceberg ploughmarks on the Bjørnøyrenna Palaeo-Ice Stream bed, Barents Sea

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Abstract

Mega-scale glacial lineations (MSGLs) are ridge-groove corrugations aligned in the direction of the former ice flow, tens of kilometers long and up to a few hundreds meters wide. They are the most striking subglacial features on the beds of former ice streams and play an important role in modulating ice flow through their influence on bed roughness and subglacial hydrology. Despite the importance of MSGLs, their formation remains enigmatic. Most studies have tended to focus on assemblages of MSGLs and their relationship to other landforms up-ice (e.g. drumlins or bedrock features in ice stream onset zones) but fewer studies have examined their characteristics and transition to other landforms towards ice stream grounding lines. In this paper we investigate the relationship between an assemblage of MSGLs and ploughmarks on the bed of the former Bjørnøyrenna Ice Stream in the SW Barents Sea, which occurs in the central part of the ice stream bed. A sample of MSGLs is used to test their potential origin, based on their metrics (width, length) and diagnostic characteristics predicted by formation theories. Results show a down-flow depth decrease of the MSGL grooves, and a shallowing tendency once they transition into ploughmarks. Their width shows an increasing tendency, which we link mostly to the strong divergence of the trough (and ice flow) downstream. The prominent continuity from linear to curvilinear features demonstrates that the grooves associated with MSGLs transition into iceberg ploughmarks. This observation is consistent with the hypothesis that the MSGLs have formed through a mechanism of ‘groove-ploughing’, at least in part. The continuity from MSGLs to iceberg ploughmarks resulted from detachment of large icebergs from the grounded ice wall or grounded ice shelf and their ploughing away from the ice margin.

1. Introduction

Fast flowing-ice streams are key components of an ice sheet and exert an important influence on their mass balance and geometry. In Antarctica, for example, they are thought to be responsible for about 90% of the overall ice discharge (Bentley and Giovinetto, 1991; Bamber et al., 2000; Bennett, 2003) and they are known to have played an important role in palaeo-ice sheet mass balance (Stokes and Clark, 2001; Ottesen et al., 2005; Stokes et al., 2016; Robel and Tziperman, 2016). The coupling between an ice stream base and the underlying sediments exerts a fundamental control on ice stream dynamics (Bell et al., 1998; Bennett, 2003; Clark et al., 2003; Smith and Murray, 2009; Stokes, in press). Basal traction (including shearing between subglacial sediment and the ice stream base, and form drag due to obstacles at the ice stream bed) is critical for regulating the velocity and trajectory of ice stream flow (Benn and Evans, 2010; Stokes et al., 2007; Tulaczyk et al., 2000; Winsborrow et al., 2016). A principal landform on the beds of former (e.g. Clark, 1993; Stokes et al., 2013; Spagnolo et al., 2014; Spagnolo et al., 2016) and contemporary ice streams (King et al., 2009) are mega-scale glacial lineations (MSGLs), which are considered a diagnostic signature of fast-flowing ice (Clark, 1993).

MSGLs are elongated ridge-groove furrows aligned in the direction of ice-flow. They are often several kilometers long, 200-300 m wide, and have amplitudes of 1 to 10 m (Spagnolo et al., 2014), although more extreme values exist. For example, at the modern Rutford Ice Stream bed, the peak-to-trough amplitude of MSGLs is up to 90 m (King et al., 2009), but the mean value (10 m) is more consistent with the palaeo-record (Spagnolo et al., 2014). The mechanisms of MSGLs formation remain debated and there are several hypotheses to explain their formation (Clark et al., 2003; Shaw et al., 2008; King et al., 2009; Fowler, 2010; Stokes et al., 2013; Spagnolo et al., 2014; Spagnolo et al., 2016). Important to this debate is whether MSGLs are constructional landforms that are somehow built up, elongated and accreted (Spagnolo et al., 2016), or whether they are formed by both depositional and erosional processes, where the material from within grooves is being excavated, leaving MSGLs on either side (e.g. Clark, 1993). Clark (1993) proposed a ‘groove-ploughing’ hypothesis that explained MSGLs as the product of basal ice keels that plough through soft sediments, like a ‘garden rake’ ploughs soil. Only a handful of studies have tested this hypothesis (although see Stokes et al., 2013; Spagnolo et al., 2014; Spagnolo et al., 2016), but a prediction would be that once the keels cross the ice stream grounding line, they would continue as iceberg-ploughmarks (Clark et al., 2003). Perhaps surprisingly, therefore, very few studies have examined the morphological relationship between MSGLs and iceberg ploughmarks in the vicinity of ice stream grounding zones, which might offer a useful test of this and other formation theories. In this paper we present a striking suite of MSGLs from the bed of Bjørnøyrenna Palaeo-Ice Stream and document clear evidence of a continuous transition from MSGL grooves to iceberg ploughmarks. This continuity is consistent with the notion that these MSGLs were formed through groove-ploughing.

1.1. Previous work on mega-scale glacial lineations (MSGLs)

MSGLs were first identified on Landsat images in Canada, and were initially thought to be a separate group of bedforms, much larger in length than drumlins or megaflutes (Clark, 1993), although more recent work suggest they lie at one end of a bedform continuum (Ely et al., 2016). This continuum is directly related to ice velocity and also includes ribbed moraines and drumlins (Aario, 1977a; Ely et al., 2016). MSGLs typically display a spatial coherency within particular ice-flow assemblages, such as their exceptional parallel alignment (similar orientation), close proximity and relatively even spacing, and similar morphometry (Clark, 1993, 1999; Spagnolo et al., 2014; 2016).

The size and shape of MSGLs, such as their length, relief and orientation, have been used for various interpretations regarding ice stream trajectory, relative ice velocity, erosional potential and sediment transport (Clark, 1993; Jakobsson et al., 2012a; Ó Cofaigh et al., 2013; Stokes et al., 2013; Spagnolo et al., 2014; Barchyn et al., 2016; Spagnolo et al., 2016). Assemblages of MSGLs revealed on exposed beds of former ice streams also provide insight into their past dynamics and can contribute to our understanding of future changes in contemporary ice streams (Holt et al., 2006; Nitsche et al., 2013; Margold et al., 2015; Patton et al., 2015; Stokes et al., 2016).

Many examples of MSGLs have been identified on the beds of palaeo-ice streams (e.g. Clark, 1993; Ottesen et al., 2005; Dowdeswell et al., 2010; Hogan et al., 2010; Winsborrow et al., 2010; Livingstone et al., 2012; Stokes et al., 2013; Bjarnadóttir et al., 2014; Spagnolo et al., 2014), yet their origin remains unclear (Clark, 1993; Clark et al., 2003; Fowler, 2010; Ó Cofaigh et al., 2010). Given the widespread association of MSGLs and rapid ice flow, understanding the processes which contribute to their formation would represent a significant advance in our understanding and ability to model subglacial processes and erosional potential of ice streams (Stokes, in press). The largely undisturbed, marine-based Bjørnøyrenna Palaeo-Ice Stream bed, represents an ideal location to study processes of MSGLs formation and can be used as a tool to understand modern ice streams in Antarctica and Greenland (Andreassen et al., 2014; Patton et al., 2016).

1.2. Formational theories

Several theories for MSGLs formation have been proposed, including subglacial till deformation (Clark, 1993), groove-ploughing (Clark et al., 2003), erosion by subglacial floods (Shaw et al., 2008), and a flow instability of subglacial meltwater that relates to the formation of rills (Fowler, 2010).

Clark (1993) was the first to formally identify and name MSGLs, and proposed their formation mechanism to be similar to that forming other ice-moulded landforms, such as drumlins (cf. Boulton and Hindmarsh, 1987). His initial ideas suggested that MSGLs might form as a result of fast-flowing ice, deforming and eroding sediments subglacially in a streamlined manner, similar to that proposed to explain drumlin formation (Boulton and Hindmarsh, 1987). The initiation of the deformation was suggested to occur around substrate irregularities, with ice-flow velocities and duration of the flow as controlling factors (Clark, 1993). Therefore, MSGLs would be part of a subglacial bedform continuum, and according to this theory may likely evolve from attenuation and deformation of drumlins, under high strain rates and high sediment supply (Clark, 1993; Stokes et al., 2013).

The groove-ploughing mechanism of formation (Tulaczyk et al., 2001; Clark et al., 2003) suggests that these landforms are dependent on the presence of longitudinally oriented irregularities at the ice stream base (keels), which form as the ice stream passes over a rough bed upstream or through lateral compression of the ice stream. These protuberances at the ice stream base will be further amplified as the ice stream converges (Tulaczyk et al., 2001; Clark et al., 2003). The keels will plough through the underlying sediments, producing a grooved surface, as the ice stream moves over the weaker till. The theory perceives MSGLs as mainly erosional features, with the neighbouring ridges being a by-product of the ploughing of the keel (Clark et al., 2003; Ó Cofaigh et al., 2005).

The groove-ploughing hypothesis makes predictions related to MSGL morphology and the nature of their occurrence. One prediction is that there will be a downstream decrease in the depth of the MSGLs grooves, due to melting of the keels at the ice stream base as they plough sediments. Depending on the properties of ice and/or the weakness of sediments, the reduction in groove-depth might be considerable or minimal (Clark et al., 2003). The theory further predicts that MSGLs should be located downstream from areas where basal keels are produced (e.g. strong convergence zone or bedrock features). Another important factor for the generation of ice keels is the roughness at the ice stream base, which should be greater across the ice stream than along the flowline. Lastly, the grooves at the inferred grounding line and downstream from there may display certain sinuosity and changes in direction, as the ungrounded ice will be laterally much less stable (Clark et al., 2003). As noted above, these predictions have rarely been tested explicitly, although qualitative arguments have been proposed that both support (Tulaczyk et al., 2001; Stokes and Clark, 2003; Ó Cofaigh et al., 2005; Ó Cofaigh et al., 2013) or refute the theory (King et al., 2009; Spagnolo et al., 2016). In some case studies, authors have concluded that groove-ploughing may be just one of the processes involved in their generation, often suggested to modify existing lineations, rather than creating them (e.g. Ó Cofaigh et al., 2002; Ó Cofaigh et al., 2005; King et al., 2009; Stokes et al., 2013). The main evidence against groove ploughing is that MSGLs have in some cases been observed to initiate within grooves (King et al., 2009; Stokes et al., 2013), bifurcate, merge, or occur in areas distant from any upstream bedrock structures that may have shaped the ice base (Ó Cofaigh et al., 2005). Some measurements of their width have also revealed a regularity along flow (Clark, 1993; Stokes et al., 2013), but sometimes the width increases downstream (Ó Cofaigh et al., 2005), contrary to predictions. Amplitude increases have also been observed in a number of cases (Ó Cofaigh et al., 2005). Thus, most of the empirical studies involving MSGLs morphology and their formation point to groove-ploughing as a transient and localised process (Ó Cofaigh et al., 2002; Ó Cofaigh et al., 2005; Ó Cofaigh et al., 2013; Stokes et al., 2013).

The meltwater flood theory (Shaw, 1983; Shaw et al., 2008; Shaw and Sharpe, 1987) is, perhaps, most controversial and suggests that a range of subglacial bedforms including MSGLs, relate to discharge of catastrophic amounts of turbulent subglacial meltwater. This theory envisages subglacial bedform generation by infilling of subglacial cavities and/or erosion of inter-bedform areas. This theory has been questioned for a number of reasons, not least because of the large volumes of water that are required (Clarke et al., 2005), but also from observations of flutings on modern glacier forelands (Evans and Twigg, 2002), and drumlins and MSGLs actively forming beneath contemporary ice streams (Smith et al., 2007; King et al., 2009) in the absence of large subglacial meltwater discharges.

More recently, a rilling instability theory has been proposed (Fowler, 2010), based on mathematical modelling of the subglacial hydrological system. The theory suggests that meltwater at the ice-bed interface is unstable and organizes into several narrow streams (rills), eroding grooves separated by ridges. Model simulations were able to produce longitudinal ‘rolls’ aligned in ice flow direction, with modelled dimensions (length 52.9 km, width 394 m) of the same order of magnitude as some empirical MSGLs observations (e.g. Clark, 1993; Andreassen and Winsborrow, 2009; Piasecka et al., 2016). However, the range of MSGL dimensions reported in literature is large (lengths from <1 km (Graham et al., 2009; Winsborrow et al., 2012) up to 180 km (Andreassen et al., 2007; Andreassen et al., 2008) and widths from <40 m (Stokes et al., 2013) up to 5 km (Andreassen et al., 2007), and the modelled values are highly dependent on particular parameters chosen for the experiment.

In addition to the rilling theory, it has been proposed that of spiral flows in basal ice (Shaw and Freschauf, 1973; Schoof and Clarke, 2001) may lead to undulations on the ice stream bed. These spiral flows were proposed to excavate longitudinal grooves and transport the eroded sediments transversely upwards, creating ridges at their sides (Schoof and Clarke, 2001). This hypothesis was initially developed to explain the presence of much smaller flutes and was supported by the observation of ‘herring-bone’ sediment distribution patterns in mega-flutings, suggesting transverse transport patterns towards ridge crests (Rose, 1987). This theory is similar to the groove-ploughing and meltwater flood theories in the sense that they all assume an erosional-depositional origin of MSGLs (Clark et al., 2003; Shaw et al., 2008).

1.3. A subglacial bedform continuum

The hypothesis of a subglacial bedform continuum invokes morphological relationships between dimensions of different subglacial bedform populations (transverse ribs and ridges, and elongated lineations), which often display a gradual transition downstream (Aario, 1977a, b; Rose, 1987; Clark, 1993; Ely et al., 2016). The continuum is thought to be dependent on ice flow velocity, with longer bedforms being formed through a higher velocity of ice flow (Aario, 1977b; Stokes et al., 2013). Although hypothesized for some time and based on only limited observational data (e.g. Aario, 1977a, b; ; Rose, 1987), recent work by Ely et al. (2016) analysed > 96,000 bedforms to clearly demonstrate a link between the morphology of ribbed moraines, drumlins and MSGLs. Thus, a body of evidence has emerged which suggests that MSGLs are at one end of a spectrum of subglacial bedforms that includes ribs, circular bedforms, drumlins and MSGLs (Ely et al., 2016), with the primary control being ice velocity (Barchyn et al., 2016). However, very little work has considered the transitional zone between MSGLs and other features at ice stream grounding lines.

2. Study area and dataset

2.1. Study area

The study area is located in the central part of Bjørnøyrenna (Bear Island Trough), SW Barents Sea (Fig.1). During the Last Glacial Maximum (~21 ka BP in this region), the area was occupied by the largest ice stream of the Barents Sea Ice Sheet (BSIS) – the Bjørnøyrenna Palaeo-Ice Stream (Andreassen et al., 2007; Andreassen and Winsborrow, 2009; Winsborrow et al., 2010; Patton et al., 2016; Piasecka et al., 2016). The water depth in the Barents Sea varies from <100 m in the shallow banks to >500 m in the deepest troughs (Jakobsson et al., 2012b). The bathymetry of Bjørnøyrenna ranges from 120 m to ~500 m. The topography of the trough is characterized by a slope deepening downstream with a depth difference of about 30 m between the shallowest and deepest point of the study area and a topographic step further upstream, towards the NE (Fig. 1). Laterally, the trough is bordered by shallow banks (<200 m) in the northern part which potentially created a strong convergence zone for the former ice stream (Fig.1). Farther downstream, the trough curves towards the SW and widens significantly (Fig.1).

2.2. Dataset

This study is based on a modern seafloor reconstructed by mapping the seismic seafloor reflection from a 13,000 km^2 3D seismic dataset located in central Bjørnøyrenna (Fig. 1). The data were provided by Statoil ASA and have vertical and horizontal resolution of 7.4 m, assuming velocity of 1480 m/s for water and dominant frequency 50 Hz for the seismic wave. The data quality is high. A faint NNE-SSW oriented acquisition footprint can be noticed on the reconstructed surface, but this is easily distinguishable and does not hinder interpretation. The seismic interpretation was carried out in Schlumberger Petrel 2014 software. For visualization, the interpreted surface was imported into Fledermaus DMagic v.7 and gridded to a cell size of 10 m. This surface was used by Piasecka et al. (2016) to reconstruct a detailed pattern of Late Weichselian flow-switching of the Bjørnøyrenna Palaeo-Ice Stream, largely based on the mapping of ~900 ridge-groove features, interpreted to be MSGLs, forming five distinct flow-sets. The five flow-sets, all identified on the seafloor, cross-cut and overprint each other. All five flow-sets are suggested by Piasecka et al. (2016) to have formed during the mid-phase of the last deglaciation of the Barents Sea Ice Sheet. In this paper, we use ‘’flow-set 8’’ of the five MSGL assemblages, to elucidate the processes of MSGLs formation. This is one of the youngest and is superimposed on other flow-sets (Piasecka et al., 2016). Unique to the mapped flow-sets, the linear MSGL grooves of flow-set 8 transition into curvilinear grooves. Given that this is a fundamental prediction of the groove-ploughing hypothesis (Clark et al., 2003), a key focus of our investigation was to test this MSGL formation mechanism by characterizing variations in MSGL groove amplitude and width.

3. Methods

3.1. Groove depth (amplitude)

Relative depths (amplitudes) of the lineations were extracted by mapping the highest points on the crests and the deepest points of the grooves along each ridge-groove landform in ArcMap v. 10.3 and then calculating the amplitude from absolute depth values (Fig. 2). The points of measurements were initially distributed every 5 km along the grooves. However, due to the post-glacial modification of parts of the surface, such as ploughing and glacimarine deposition (see e.g. Fig. 2), and the overprinting pattern other generations of MSGLs, some of the points located in these modified areas were shifted to obtain representative depth values. The depth values of each groove were plotted along profiles, where the y-axis represents the grooves depths and the x-axis is the distance downstream.

3.2. Groove width

The widths of the grooves were measured using visualization software Fledermaus v. 7, across eight transects for each groove, numbered 1-8 from upstream to downstream, respectively. Due to the lack of an obvious break in slope or 'shoulder' to the grooves, their width was measured as the distance between the highest points (crests) of two associated ridges (Fig. 3c). However, some of the ridges associated with the grooves were eroded or overlain by younger generations of MSGLs and ploughmarks, and their profiles sometimes have several cavities at the crests. This required a determination as to whether the cavity belongs to the groove (and for example was formed by a multi-keel iceberg) or was overprinted by ploughmarks or MSGLs at a later stage (see example in Fig. 2a). This was done based on the orientation of overprinting grooves in 3D view (Fledermaus v. 7) and any cross-cutting grooves were excluded from the measurement. Due to the overprinting patterns, some of the measurement points were slightly shifted to avoid areas overprinted by other generations of MSGLs, younger ploughmarks, in addition to areas with hemipelagic sediment infills in the grooves. Therefore, the cross-flow profiles for width measurement were not drawn as a straight line.

4. Results

4.1. Linear-curvilinear ridge-groove features

The seafloor relief surface presented in Figure 3 reveals imprints of overprinting and cross-cutting MSGLs assemblages and numerous ploughmarks (Piasecka et al., 2016). Within a large flow set of deglacial MSGLs – ‘’flow-set 8’’, described in Piasecka et al. (2016), we identified numerous features that exhibit both a linear and curvilinear nature. The flow-set has been chosen due to the best preservation of features among all flow-sets, as it is one of the youngest. There seem to be more MSGLs that exhibit transition between curvilinear and linear grooves, but most of them have been overprinted by younger ploughmarks and the continuity is, in these cases, not observable. The continuous features are described and interpreted in the following sections.

a) Description of ridge-groove features

The ridge-groove features (Fig. 4 and 5) are characterized by a linear-curvilinear continuity. They occur on the central Bjørnøyrenna seafloor and their linear orientation is thought to reflect the predominant ice flow direction of the former Bjørnøyrenna Ice Stream (Marfurt, 1998; Andreassen et al., 2008; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Piasecka et al., 2016), curving along the trough towards the SW (Fig. 3). They are characterized by a linear shape along the major part of the groove and display a prominent directional shift further downstream, where they transition into curvilinear grooves (Fig. 5 a-c). Termination of linear grooves coincides with a thin, but wide, elongated sediment accumulation, up to 10 m in relief, extending across the trough. The pattern of the grooves is, in some areas, distorted by post-glacial modification, such as sediments infilling the grooves or by chaotic patterns of overprinting ploughmarks (see Fig. 2 a). The maximum length of the linear part of the grooves is ~45 km, while the minimum length is 30 km. The maximum length of the grooves (including the curvilinear part of the groove) is ~65 km and the minimum is 41 km. Transition points from linear to curvilinear grooves were identified from directional shifts of the grooves and a noticeable change in groove depth. This occurs at an absolute water depth of about 450-460 m below sea level (bsl), except for two grooves in the southernmost part of the seafloor which are located at a higher elevation (Fig. 5c). Here the transition occurs at present water depths of 443-445 m. Some of the linear parts of the grooves terminate with an overdeepening oriented along the groove axis (Fig. 6, 8) and then the grooves get shallower, once they transition into curvilinear features. Ploughmarks initiate in the outer part of the ice marginal deposit and continue downstream. Some of them can be observed in the deeper part of the trough, away from the grounding line, where they terminate.

b) Interpretation

Based on the length, width and elongation ratio of the grooves we interpret the linear features to be mega-scale glacial lineations (MSGLs), formed through the fast flow of Bjørnøyrenna Palaeo-Ice Stream. According to a recent reconstruction of flow-switching in Bjørnøyrenna (Piasecka et al., 2016), the MSGLs assemblage was formed during one of the ice stream re-advances around 15-16 ka BP, but during overall deglaciation. We interpret the transition line in Figures 5 a-c as the former grounding line around that time and the transverse sediment accumulations as ice marginal deposits. Extent of the inferred grounding line is delimited by a bathymetric change that shows a topographic deepening of about 10-15 m in the westernmost part of the seafloor.

The MSGLs appear to terminate with keel related overdeepenings (Fig. 6), marking the initiation of each ploughmark and simultaneously indicating reach of the grounded ice. Curvilinear grooves are interpreted as iceberg ploughmarks, similarly to a previous work on this MSGLs assemblage (Piasecka et al., 2016). As such, this is, to our knowledge, the first dataset to clearly demonstrate continuity between the grooves of MSGLs and iceberg ploughmarks (Fig. 5 a-c). Some of the iceberg keels (for example 7, 8, 9, 11, 12 and 13) seem to have continued with an orientation similar to each other (Fig.7). However, others shows much more deviation and we conclude they may have been affected by oceanic currents in front of the ice margin, whereas the others were likely trapped in a dense melange of icebergs. The undulating shape of the inferred grounding line across flow reflects the configuration of the grounded ice margin and the influence of local topography (Fig. 7a).

4.2. Groove depth (amplitude)

a) Description

General trend-lines for all 13 MSGLs show continuous shallowing of the linear grooves downstream (Fig. 8). Slope gradients of the grooves are negative (implicating shallowing) and range from 26% to 3% (14.6° to 1.7°) (Fig. 8). Generally, the depths (amplitudes) of the ridge-groove features fit the definition of MSGLs from numerous settings (Spagnolo et al., 2014). Their relative depths measured between the crest of an MSGL ridge and the deepest point of the associated groove (Fig. 2 and 7) along each groove are plotted in Figure 8. Maximum amplitude values of the measured grooves is 11 m in the upstream part of the ice stream bed (groove number 11), while the minimum is less than 3 m (groove number 3). In the upstream part of the seafloor, the curves show a downstream-decreasing tendency in amplitudes until they reach the point of transition into a ploughmark (Fig. 7, white dashed line). In several cases, the depth profiles show two amplitude peaks (abrupt depth increase) upstream and downstream (grooves 1, 2 and 7). However, in most cases the upstream peak does not occur or is minimal (Fig. 8). Most interestingly, the plots show a prominent deepening in the zone where linear grooves transition into curvilinear grooves. Further downstream, the curvilinear grooves (ploughmarks) depth decreases again until they terminate.

b) Interpretation

The landform assemblage of linear-curved grooves is interpreted as mostly erosional, with associated ridges being a by-product of ploughing. The continuity from linear to curvilinear grooves is consistent with erosion by keels at the base of the grounded ice stream which evolve into iceberg keels beyond the grounding line. In the Barents Sea, the observed trough-to-crest amplitude of MSGLs varies between 5 to 10 m (Spagnolo et al., 2014). The relatively minor, yet consistent, decrease in amplitude of the MSGLs assemblage downstream could be explained by melting of the basal ice keels in the ice flow direction (see Discussion).

4.3. Groove width

a) Description

In contrast to the depth values, width of the grooves exhibit a prominent increase downstream (Fig. 9). The percentage width increase ranges from 5% (117 to 123 m for groove number 13) up to almost 390% (39 to 189 m for groove number 10), see Figure 9b. The widths of MSGLs in the upstream (1) profile vary from 39 m to 131 m. In the middle profile (5), the widths are higher and range from 83 to almost 154 m. In several cases, they are more than twice the upstream width value (groove number 7, 10, 11, 12). In the case of grooves 4 and 13, however, the value is lower in the main trunk than it is upstream, but increases again in the downstream part.

b) Interpretation

Our results show a general increase in groove width downstream. However, each profile is characterized by a high variability of MSGLs widths, with a broad range of values. MSGLs widen in the ice flow direction, but their width change is most prominent in the downstream part, which would likely represent divergent flow of the ice stream and transition of grooves into ploughmarks (Fig. 5 a-c, Fig. 6). The groove-ploughing formation of MSGLs assumes groove widths to remain constant or decrease downstream (Clark et al., 2003).

5. Discussion

5.1. Testing groove-ploughing predictions

In this section, we discuss the plausibility of a groove-ploughing origin (cf. Clark et al., 2003) for the MSGL-ploughmarks assemblage in central Bjørnøyrenna. A key observation is the clear connection/continuity between MSGLs and ploughmarks. This forms the basis for our groove-ploughing interpretation for Bjørnøyrenna MSGLs because it implies that the same iceberg keel was responsible for creating the connecting groove (MSGL) upstream.

According to predictions of the groove-ploughing theory, MSGLs should occur downstream from where the roughness elements (keels) at the ice stream base are produced (Clark et al., 2003). Typically, roughness in Bjørnøyrenna increases in higher elevations upstream and decreases in deeper basins (e.g. central Bjørnøyrenna) (Gudlaugsson et al., 2013). High bed roughness values have been reported in Bjørnøyrenna upstream from the study area and are likely associated with Triassic subcropping bedrock, which forms a prominent topographic step (Gudlaugsson et al., 2013; Henriksen et al., 2011). Immediately upstream of the studied MSGLs outcropping bedrock ridges, oriented transverse to former ice flow, have been mapped (Bjarnadóttir et al., 2014). Such bedrock undulations may have shaped the ice base, with the resulting basal keels propagating with ice movement downstream into soft-sediments areas (Clark et al., 2003). Downstream, roughness largely decreases towards deeper areas dominated by unconsolidated sediments, which coincide with the initiation of the MSGLs (Gudlaugsson et al., 2013). The area where the mapped MSGLs initiate is dominated by unconsolidated sediments with relatively low roughness.

Another factor that was likely important in contributing to the formation of the keels at the ice stream base is the strong convergence zone of Bjørnøyrenna, upstream of the studied MSGLs (Fig. 1). Based on the interpretation of Piasecka et al. (2016), the MSGLs assemblage studied herein is suggested to have formed during deglaciation between 15-16 ka BP. At this time, the ice stream flow trajectory in the study area was entirely constrained within the Bjørnøyrenna trough (Piasecka et al., 2016). Thus, strong lateral compression exerted on the converging ice as it moved through this narrow zone could have created longitudinal structures through shear strain and longitudinal foliation within the ice mass (Clark et al., 2003; Glasser et al., 2015), which further propagated downstream with the ice stream movement. Similar structures, called 'flow stripes', often occur on ice stream surfaces and are created through three-dimensional folding of the ice (Glasser et al., 2015), but may also be a surface expression of bedrock undulations at the ice stream bed (Gudmundsson et al., 1998).

A downstream depth decrease of the linear grooves is consistent with groove-ploughing predictions, and is likely an indication of gradual, frictional-related heating and melting of the keels. The presence of ridges at the sides of the grooves suggests they could have formed through squeezing of sediments, eroded from the grooves, away and upwards from the ploughing protuberances and filling in the convex spaces in basal ice, analogous to raking of soil (Clark et al., 2003). Deeper basins of central Bjørnøyrenna are dominated by a layer of unlithified and water-saturated sediments of low roughness (Solheim and Kristoffersen, 1984; Solheim et al., 1990), which are ~60 m thick in the study area. These sediments are mostly of subglacial-glacimarine origin, but are covered by a thin layer of hemipelagic sediments (Solheim and Kristoffersen, 1984). Gradients of the groove depth trend lines (from 26% to 3%) (Fig. 8), suggest a maintenance of ice keels over considerable distances, which could be an indicator of high ice flow velocities and/or the presence of low yield strength, easily deformable sediments at the bed (Clark et al., 2003; Gudlaugsson, 2013). Both are consistent with ice streaming.

The width of the curvilinear furrows show a downstream increase (widening), which is a key prediction of the 'groove-ploughing' theory because 'sharper' keels should melt out and become broader and flatter. Indeed, widening of the linear grooves downstream can result from a combination of extensional ice flow in the divergence zone and gradual melting of the keels through ploughing of the sediments (frictional heating) (Benn and Evans, 2010). Consistent with groove-ploughing predictions, the spacing between the MSGLs slightly increases downstream, most likely due to ice stream flow divergence. Although the spacing increase is not large, it becomes more prominent with the initiation of curvilinear grooves at the inferred grounding line. Transition into ploughmarks points to activity of free icebergs, detached from the grounded ice margin and scouring at present water depths of ~450 m (Fig. 7). At that time, the relative sea level was 110-115 m less than it is today, while ice thickness was at least twice the water depth (Andreassen et al., 2017; Patton et al., 2016). The continuity of MSGLs and ploughmarks is consistent with the groove-ploughing theory, predicting a sharp change in shape of the grooves, as well as directional shifts of grooves, at the inferred grounding line.

5.2. MSGL-ploughmark transition at the grounding line

The abrupt shift in groove orientation and the deepening of the groove at the end of each MSGL (Fig. 6) likely marks the grounding line and the transition from a MSGL groove to an iceberg ploughmark (Fig. 5 a-c). The increase in groove depth at the end of each MSGL, where they transition into ploughmarks, is somewhat enigmatic, but may have resulted from the impact of an iceberg being abruptly detached from the grounded ice front, whereupon it loses its lateral buttressing and temporarily sinks and grounds on the seafloor (King et al., 2016). Although the bathymetry seems deep in the area (present depth 450 m bsl), the thickness of the ice margin was enough for detached icebergs to ground (Andreassen et al., 2017; Patton et al., 2015; 2016). Such deep-water iceberg ploughing is commonly observed on the Arctic continental shelf down to at least 500 m water depth, but there are examples of iceberg ploughing in depths reaching 850 m (Vogt et al., 1994).

Palaeo-climate reconstructions indicate that as the ice margin entered deeper water, it may have been affected by the influx of Norwegian Atlantic Current (>3°C) during the late glacial around 16 ka BP (Ślubowska-Woldengen et al., 2008), and which may have undercut the ice at its base. The presence of the warm current at the ice front and deepening of the trough downstream along its axis, could have prevented formation of an ice shelf, instead exposing an ice wall (Pollard et al., 2015). After calving, some of the icebergs seemed to follow the slight overdeepening in the westernmost part of the seafloor, perhaps still influenced by the warm Atlantic Current (Ślubowska-Woldengen et al., 2008). These processes at the grounding line are illustrated in Fig. 10, which shows a conceptual model of how the MSGL grooves transition into iceberg ploughmarks. Configuration of the inferred grounding line might have been determined by the distribution of surface and bottom crevasses, as well as the regional topography. There is no data regarding presence of an ice shelf in the study area, however, we may imply a grounded ice stream terminus (as evidenced by the continuity of grooves).

5.3. Comparison of results with other theories of MSGL formation

We consider groove-ploughing to be the primary mechanism in formation of the subset of Bjørnøyrenna MSGLs described in this study, largely because of the strong observational evidence that shows that grooves associated with MSGLs transition into iceberg ploughmarks, the latter being clearly erosional. Given that not all MSGLs within the dataset show this bedform continuum, we do not suggest that groove-ploughing is the only mechanism for MSGL formation. However, we clearly document this to be one of the mechanisms by which MSGLs can be formed and now evaluate other possible mechanisms of MSGL formation in light of our observations.

The sediment deformation theory (Clark, 1993), is unlikely to be the primary mechanism for the Bjørnøyrenna MSGLs-ploughmarks continuum because the iceberg ploughmarks are clearly erosional, and can be traced upstream into the grooves that lie between MSGLs. Inherent to traditional views of the deforming bed theory (e.g. Boulton and Hindmarsh, 1987), is that sediment deformation occurs around substrate irregularities that seed the glacial lineation (e.g. drumlins or MSGLs). Such substrate irregularities at the stoss end of MSGLs are not obvious in our datasets and, indeed, the start and end of the MSGL ridges either side of the grooves are not always easy to identify (cf. Spagnolo et al., 2014). Moreover, under conditions of a pervasively deforming bed, it might be expected that drumlins should form upstream of the MSGLs in the onset zone of the ice stream (e.g. showing a bedform continuum with an increasing degree of streamlining and elongation down-ice as velocities increase). However, no drumlins have been mapped upstream of the study area in Bjørnøyrenna. There are, however, some observations of ‘shoulders’ on the flanks of grooves, which may suggest that material is locally ploughed from within the groove and pushed and squeezed up towards ridge crests (Clark et al., 2003). In some senses, this is a form of deformation that is associated with the groove-ploughing process (cf. O’Cofaigh et al., 2013), but we do not consider it a major process in the formation of the intervening ridges (MSGLs), which we instead view as largely erosional remnants.

The mega flood theory (Shaw et al., 2008) implies the presence of meltwater bedforms (meltwater channels, eskers, tunnel valleys) in association with the assemblage of MSGLs. However, no such forms have been observed upstream of the study area (Bjarnadóttir et al., 2014). Landforms in upper Bjørnøyrenna are mostly associated with fast ice stream flow or ice stream stagnation, with no signs of catastrophic meltwater release (Andreassen et al., 2014; Bjarnadóttir et al., 2014). Two flow-sets of MSGLs overprint our sample assemblage (Piasecka et al., 2016) and we find it unlikely that multiple generations of flow-sets could be preserved if they were formed by catastrophic floods. Therefore, we suggest that the MSGLs in Bjørnøyrenna are formed by a mechanism unrelated to catastrophic meltwater floods.

The rilling instability theory for MSGL formation (Fowler, 2010) has thus far been difficult to test empirically. There is no doubt that meltwater pressure and, hence, porewater pressure in sediments, has had a key effect on the generation of the Bjørnøyrenna flow-sets, and likely facilitated the fast ice flow. Moreover, the rilling instability could explain how grooves are excavated by a combination of ice-keel ploughing and localized meltwater erosion within the groove. It is plausible therefore that when this undulating base comes afloat the keels within grooves also create ploughmarks. However, the theory predicts a regular distribution of MSGLs with ‘preferred’ dimensions (Fowler, 2010). The dimensions of the MSGLs within the Bjørnøyrenna flow-set are broadly consistent with these predictions, but show a wider range in both width and vertical amplitude and their distribution is not obviously regular and awaits further quantitative analysis.

To summarise, we suggest that MSGLs are likely formed through a combination of several mechanisms, such as groove-ploughing (Clark et al., 2003), sediment deformation along the flanks of the grooves, and perhaps focussed meltwater erosion within the grooves (Fowler, 2010). However because there is such a clear continuity between the erosional iceberg ploughmarks and the grooves upstream that sit between the MSGLS, we suggest that groove-ploughing is the dominant formation mechanism of the landform assemblage.

6. Conclusions

MSGLs are important to understanding ice stream dynamics, but there is little consensus regarding their formation (Stokes et al., 2013; Spagnolo et al., 2016; Stokes, in press). Conclusions of numerous studies from different palaeo-ice stream beds raise the possibility of a complex origin of MSGLs (e.g. King et al., 2009; Ó Cofaigh et al., 2013; Stokes et al., 2013; Spagnolo et al., 2016), often indicating groove-ploughing as a secondary or a localised process contributing to their formation (Stokes et al., 2013; Spagnolo et al., 2014). In this paper, we present observations of MSGLs from the bed of the former Bjørnøyrenna Ice Stream, SW Barents Sea that clearly show that a subset of these landforms exhibit a transition from an assemblage of grooves associated with MSGLs to iceberg ploughmarks. This points to groove-ploughing of ice keels as primary dominant formational process for this subset of MSGLs. The linear part of the grooves is inferred to have formed through groove-ploughing of sediments by ice keels at the ice stream base (cf. Clark et al., 2003). This is supported primarily by the continuity from linear (MSGLs) to curvilinear grooves (ploughmarks) and the downstream-decreasing depth of the grooves and the slight downstream-increase in spacing of the grooves. Ice base undulations could have formed in higher roughness zones in northern Bjørnøyrenna and are likely to have been amplified in the strong convergence zone upstream from the study area. Soft, weak sediments in the deeper parts of central Bjørnøyrenna could sustain fast ice flow and allow propagation of the ice keels farther downstream. In summary, we document clear evidence for MSGLs in central Bjørnøyrenna forming by a groove-ploughing mechanism, evidence that in some settings this is an important subglacial process.

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Figure captions:

Fig. 1 Overview map of the study area in central Bjørnøyrenna (Bear Island Trough), SW Barents Sea. The black outline indicates the location of the seafloor image presented in Fig. 3. Orange dashed lines show the extent of the trough with the convergence zone in its northern part, diverging downstream (blue dashed line). Orange arrows indicate ice flow direction of the Bjørnøyrenna Palaeo-Ice Stream during deglaciation. The background map is taken from IBCAO v. 3.0 (Jakobsson et al., 2012b). Inset figure shows the extent of the Barents Sea-Fennoscandian Ice Sheet during its Last Glacial Maximum (blue outline) and the black box shows the location of the overview map.

Fig. 2 Illustration of ridge-groove amplitude (depth) measurements. (a) A ridge-groove curvilinear feature. Inset shows the location of the figure on the seafloor map. (b) Red point indicates the crest of the associated ridge (highest point), the blue point is the deepest value within the groove. (c) Profile x-y showing depth difference between the deepest and the shallowest point.

Fig. 3 (a) Shaded relief surface of the seafloor reconstructed from 3D seismic data. Black arrows indicate the orientation of acquisition artifacts. (b) Seafloor showing mapping of the complete MSGLs assemblage, displaying some linear-curvilinear characteristics where MSGLs grooves transition into ploughmarks. (c) Illustration of groove width measurement. The black arrows indicate distance between two MSGL ridge crests

Fig. 4 Map of the Bjørnøyrenna seafloor showing the linear-sinusoidal grooves assemblage used in this study (black lines). Black rectangles mark the location of zoom-ins shown in Figure 5, while white rectangles indicate the location of close-ups of transition points (deeper iceberg 'pits') initiating curvilinear grooves (Fig. 6).

Fig. 5 A magnified view of linear grooves transitioning into curvilinear ploughmarks (for location see Fig. 4). White arrows point to the linear part of the grooves (MSGLs), while the black arrows point to the sinusoidal part (ploughmarks). The orange circles mark the approximate point of transition and the dashed white lines represent the inferred grounding line based on that transition.

Fig. 6 Examples of pits made by ploughing keels (dashed black circles) which mark the transition from linear to curvilinear groove (for location see Fig. 4). Along-groove profiles (orange line) show an abrupt depth change at the transition from linear to curvilinear groove. Blue dashed vertical lines on the profiles mark the point along the groove where the MSGL transitions into a ploughmark.

Fig. 7 Ridge-groove features showing transition from linear to curvilinear shape. The orange dots indicate depth (amplitude) measurement points along each ridge-groove (Fig. 8). The white dashed line indicates the transition points from linear to curvilinear grooves (presumably the former grounding line).

Fig. 8 Stacked groove amplitude curves showing the depth-decreasing trend of the studied grooves. Vertical axis represents depths of the grooves (in meters). The horizontal axis indicates subglacial and proglacial part of the grooves, inferred from the directional shift of linear into curvilinear grooves and their sudden depth increase. The dashed vertical line marks the inferred grounding line. Numbers to the left indicate the designation number of a groove and correspond to the numbers of MSGLs in Fig. 7.

Fig. 9 (a) Analysis of groove widths. Numbers 1-8 indicate cross-profile locations (transect numbers on x-axis), where (1) is the upstream profile and (8) is the downstream profile (b) Values of all groove widths (in meters) plotted for the eight cross-profiles. Each colour indicates one MSGL, from number 1 to 13.

Fig. 10. (a) Conceptual model of the MSGLs-ploughmark formation through slab calving at a grounded ice cliff. Numbers 1-5 indicate particular stages of ice flow and calving. 1 – Bjørnøyrenna Palaeo-Ice Stream readvance towards the deeper parts of Bjørnøyrenna; 2 – the grounding line shifts towards the deeper basin in central Bjørnøyrenna and crevasses start to form; 3 – extensional strain due to divergent flow and tensile stresses near the terminus resulting from depth differences (Δh) lead to fracture formation; 4 – the fracture eventually connects surface and bottom crevasse, possibly leading to slab calving; 5 – the detached iceberg falls to the deeper water, forming a pit (black circle) through keel impact, and scours the seafloor as it moves downstream, creating a ploughmark (dark green curve). Transition line indicated with red dashed line. (b) A simplified illustration of the Bjørnøyrenna Palaeo-Ice Stream groove-

ploughing (modified from Clark et al., 2003). The dashed lines show grooves created by the ice stream keels during the readvance.

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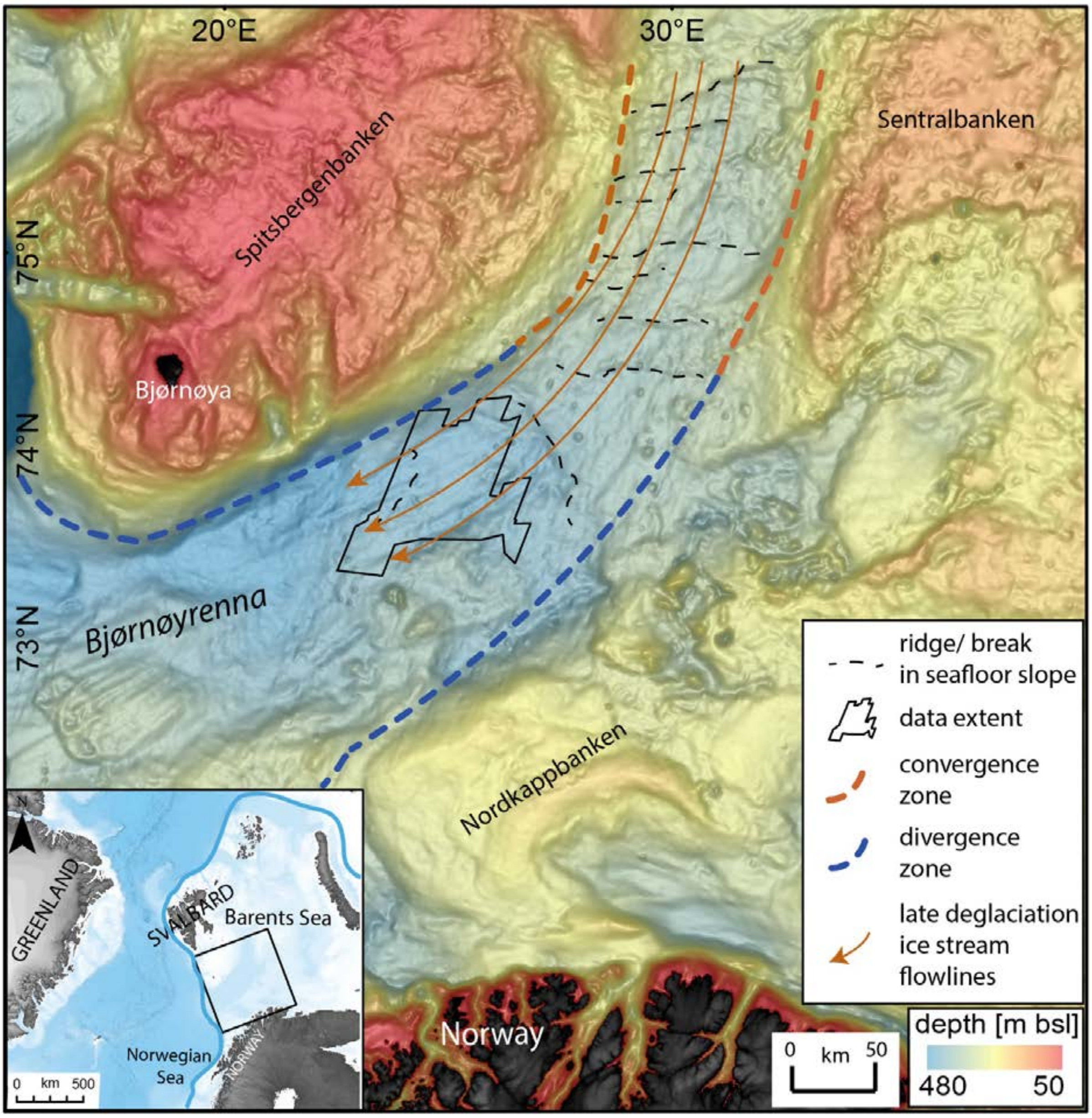
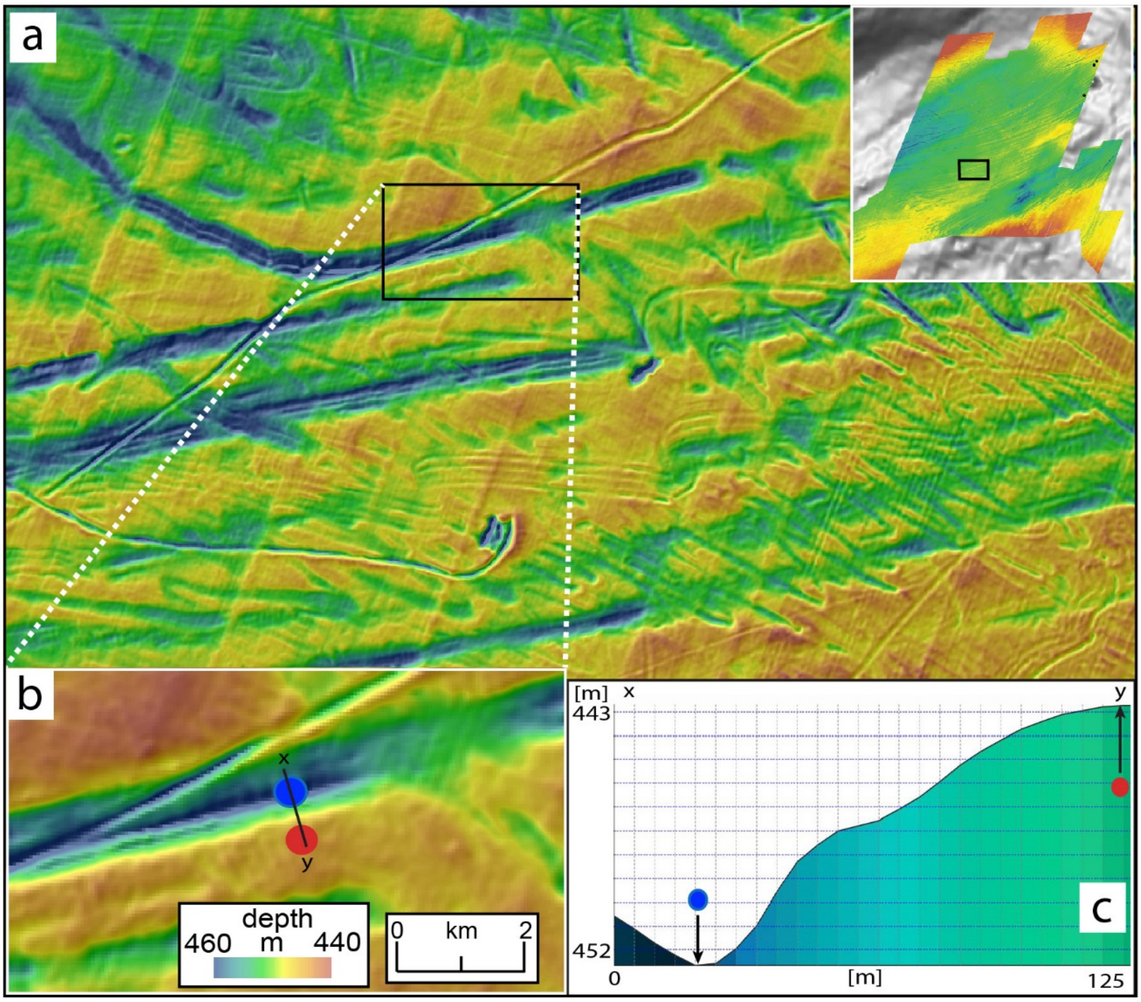
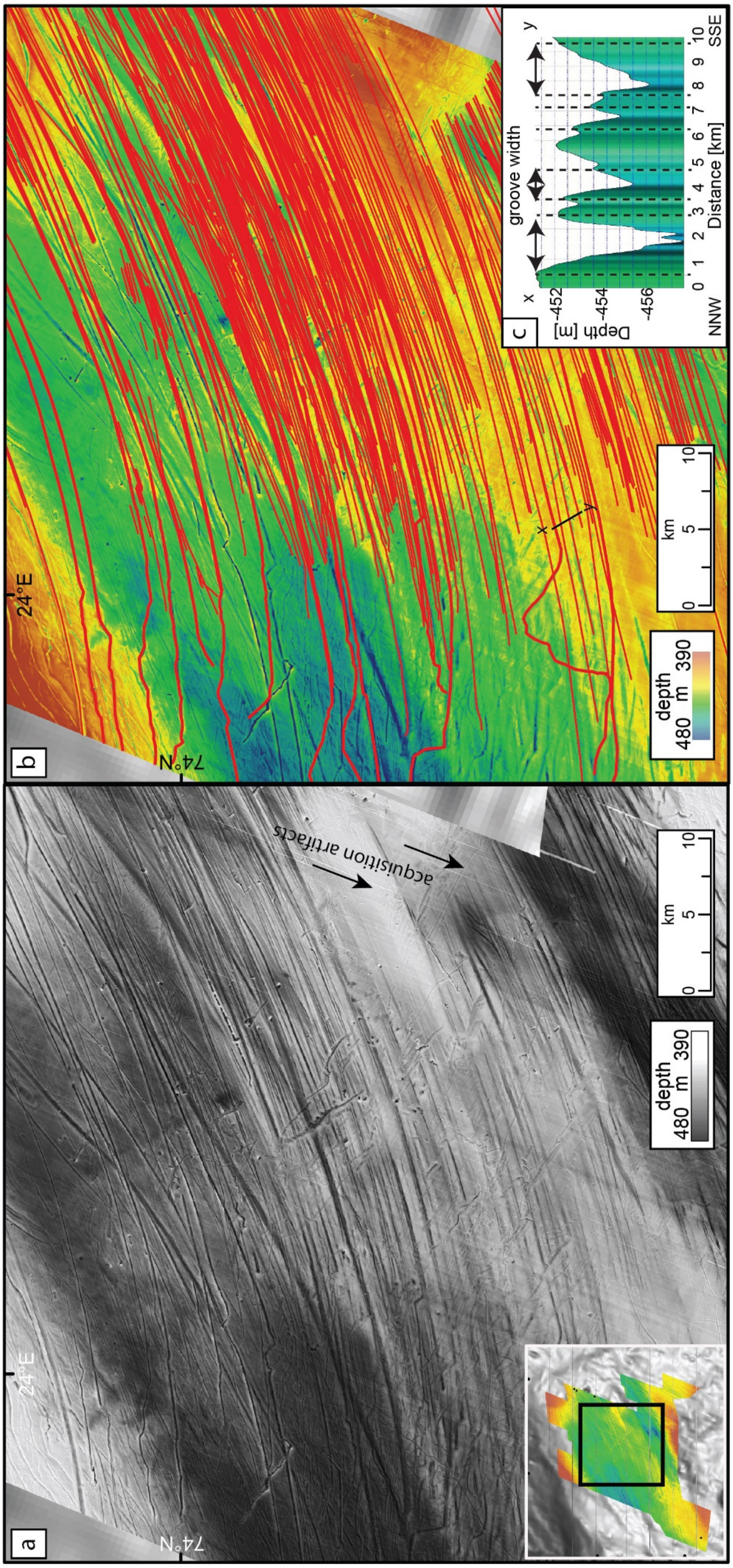
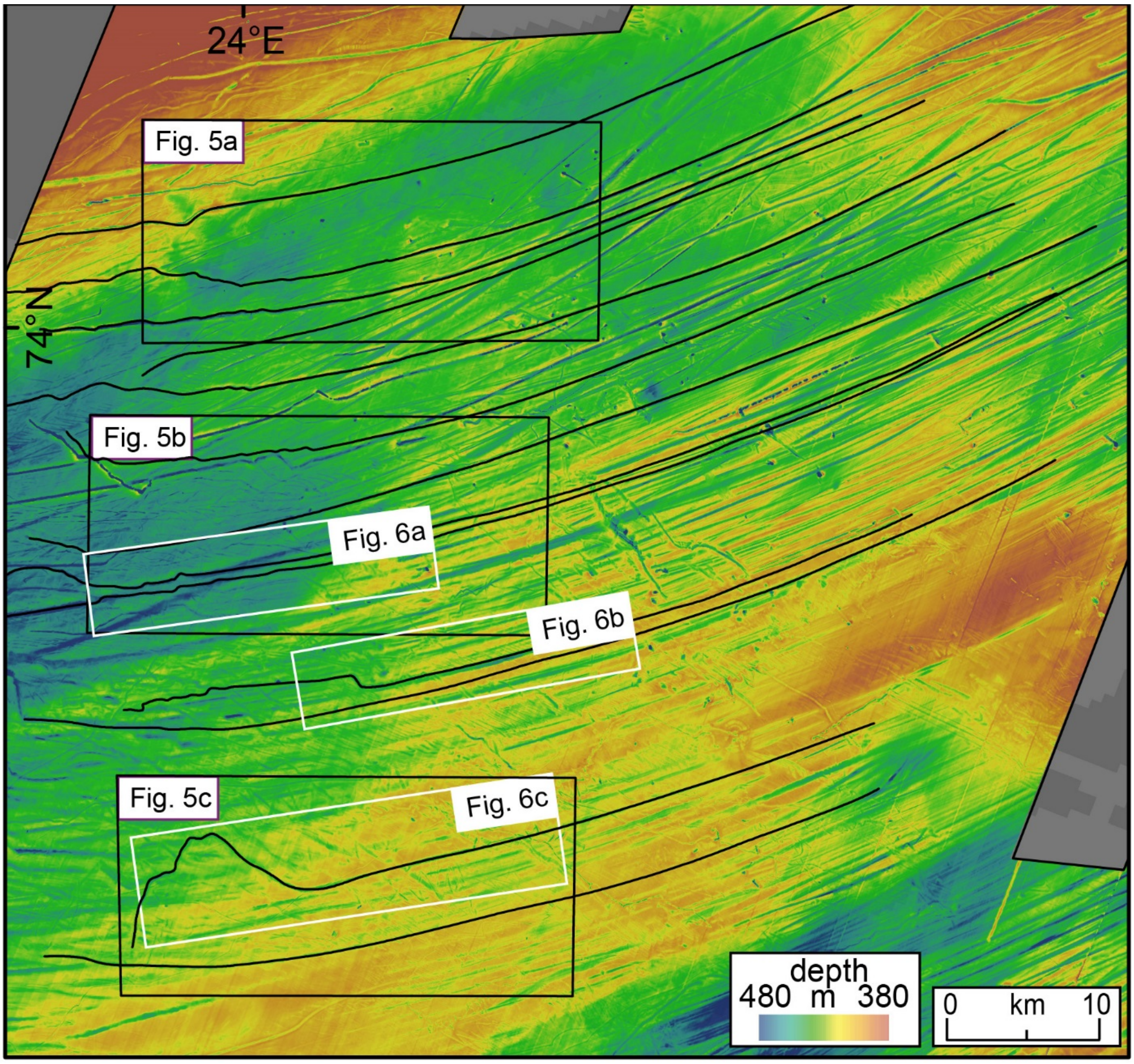

20°E
30°E
Sentralbanken
Spitsbergenbanken
75°N
Bjørnøya
74°N
73°N
Bjørnøyrenna
Nordkappbanken
ridge/ break in seafloor slope
data extent
convergence zone
divergence zone
late deglaciation ice stream flowlines
GREENLAND
SVALBARD
Barents Sea
Norwegian Sea
NORWAY
0 km 500
Norway
0 km 50
depth [m bsl]
480
50

820 



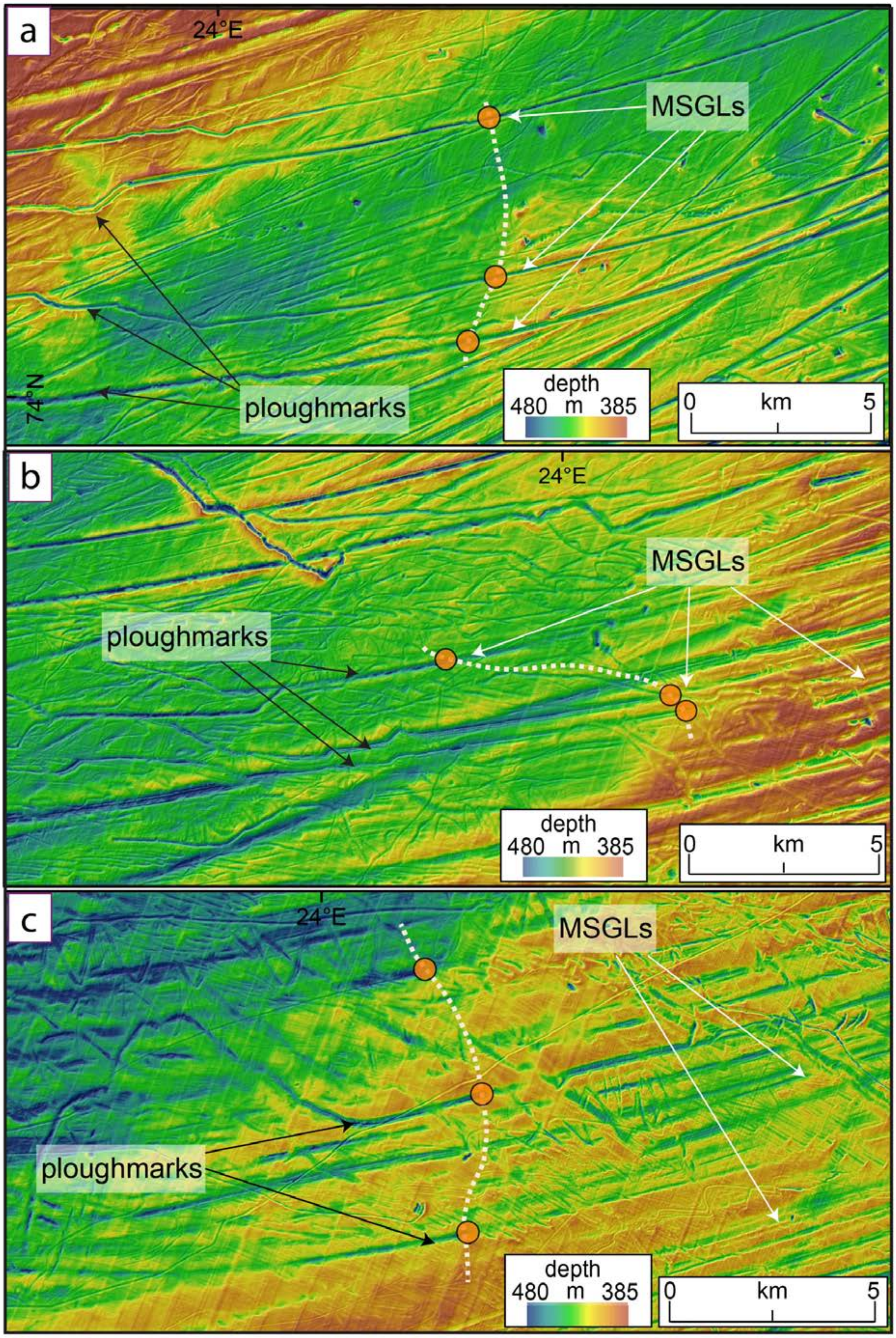
a
b
c
24°E
74°N
depth
m
480
390
km
0
5
10
acquisition artifacts
x
y
groove width
Depth [m]
-452
-454
-456
Distance [km]
0 1 2 3 4 5 6 7 8 9 10
NNW
SSE

822 

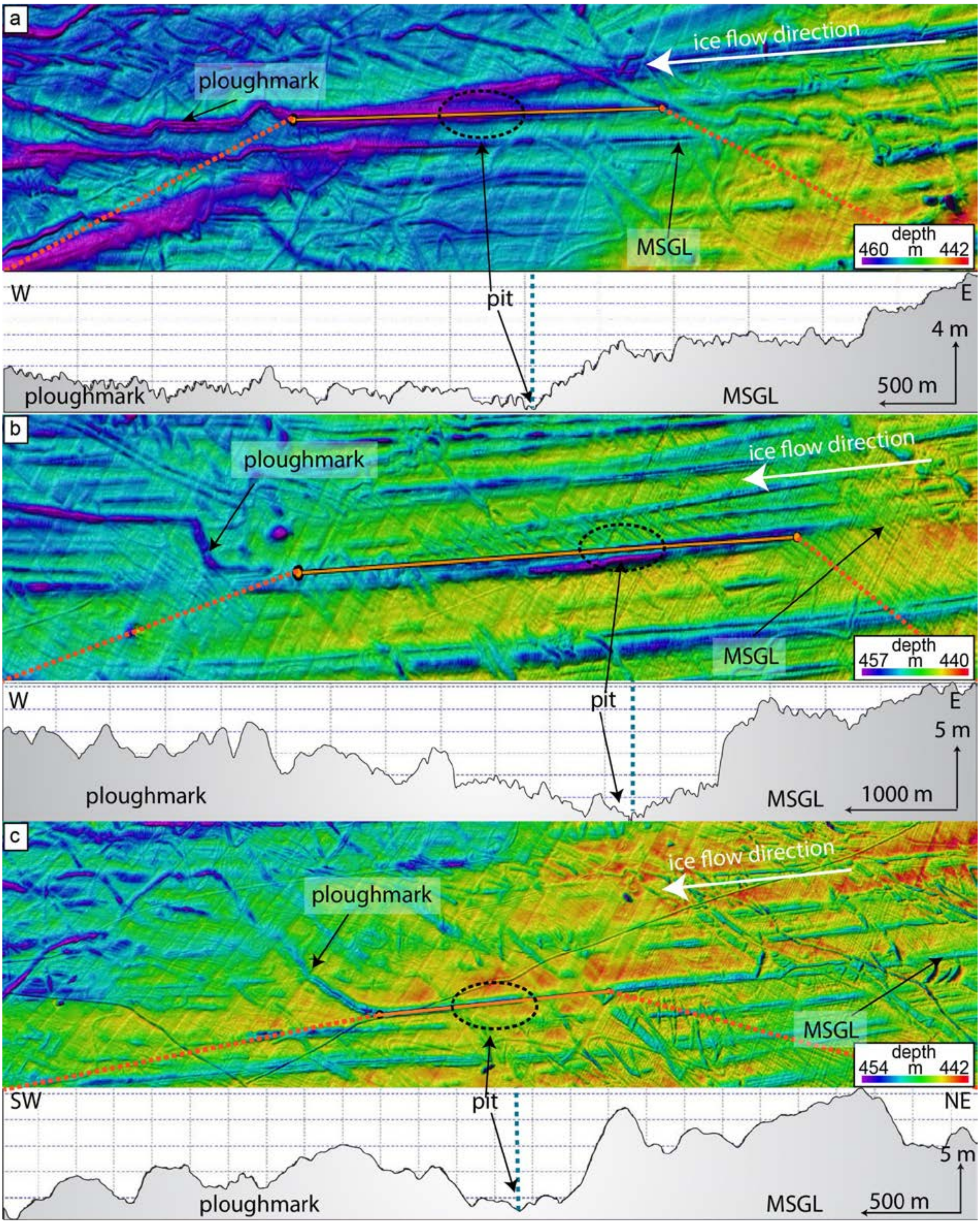
24°E
74°N
Fig. 5a
Fig. 5b
Fig. 6a
Fig. 6b
Fig. 5c
Fig. 6c
depth
480 m 380
0 km 10

823

824

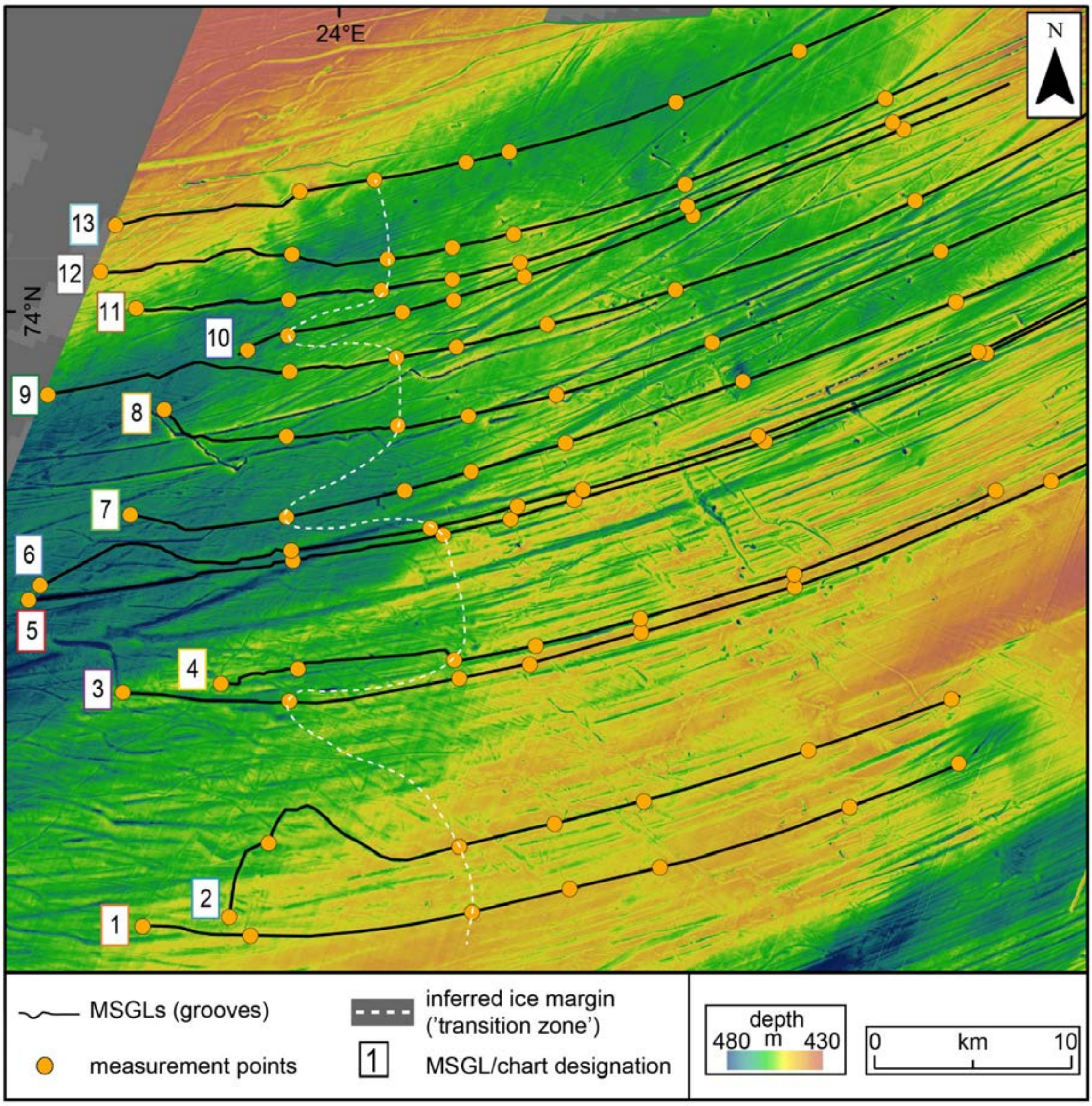


a
24°E
MSGLs
74°N
ploughmarks
depth
480 m 385
0 km 5
b
24°E
MSGLs
ploughmarks
depth
480 m 385
0 km 5
c
24°E
MSGLs
ploughmarks
depth
480 m 385
0 km 5

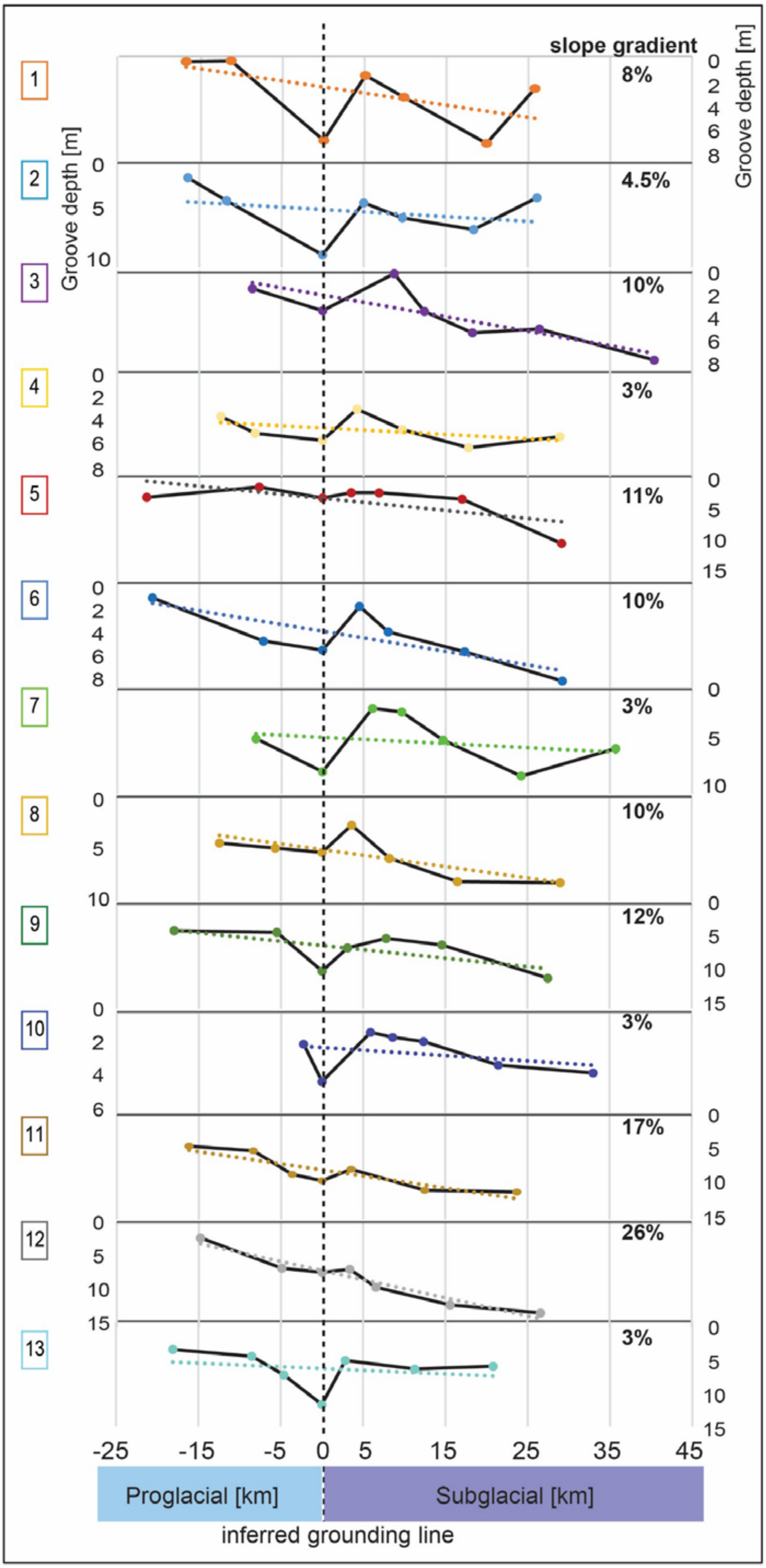
825 

a
ice flow direction
ploughmark
MSGL
depth
460 m 442
W
E
pit
4 m
500 m
ploughmark
MSGL
b
ploughmark
ice flow direction
MSGL
depth
457 m 440
W
E
pit
5 m
ploughmark
MSGL
1000 m
c
ice flow direction
ploughmark
MSGL
depth
454 m 442
SW
NE
pit
5 m
ploughmark
MSGL
500 m

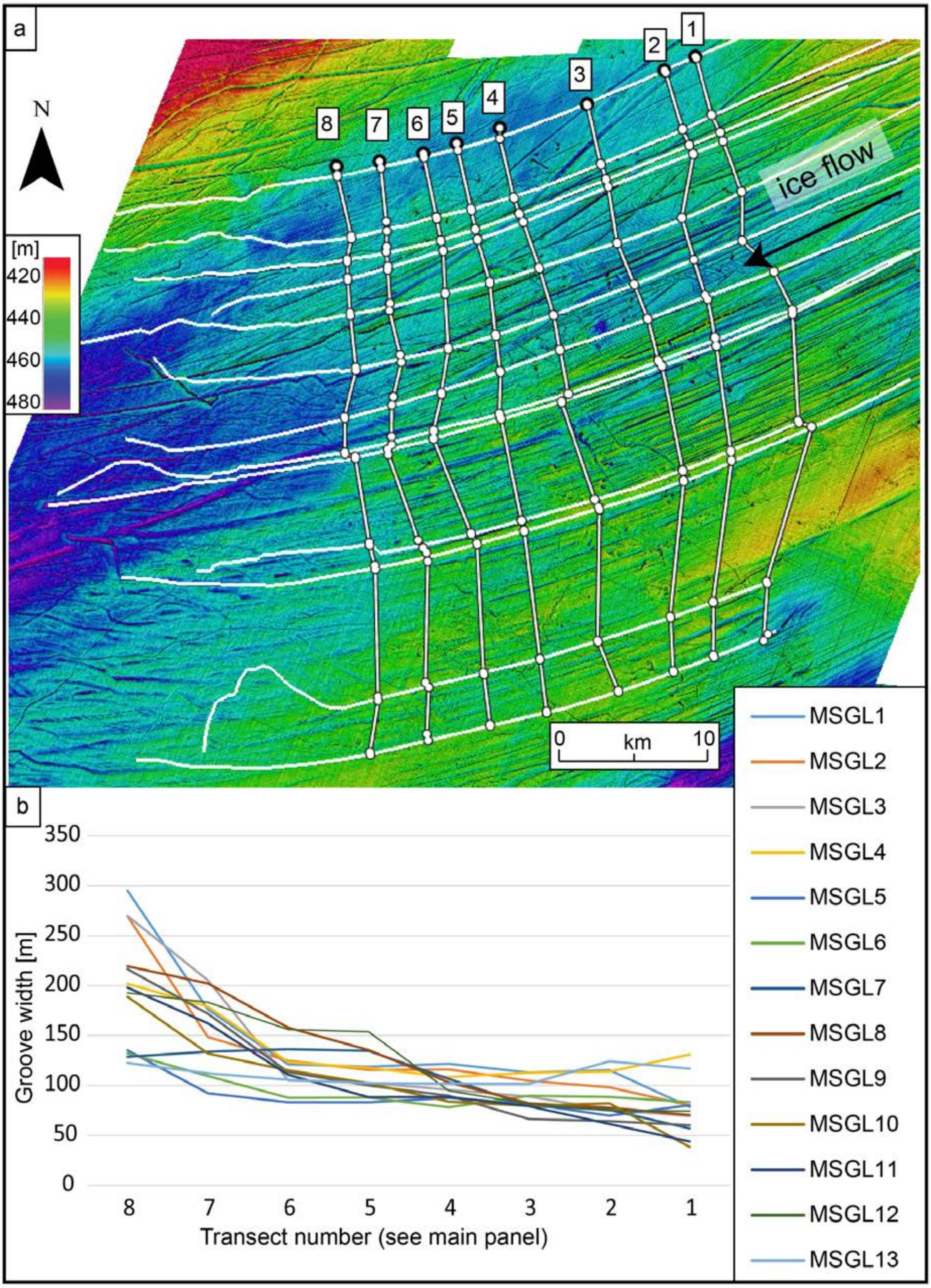
826

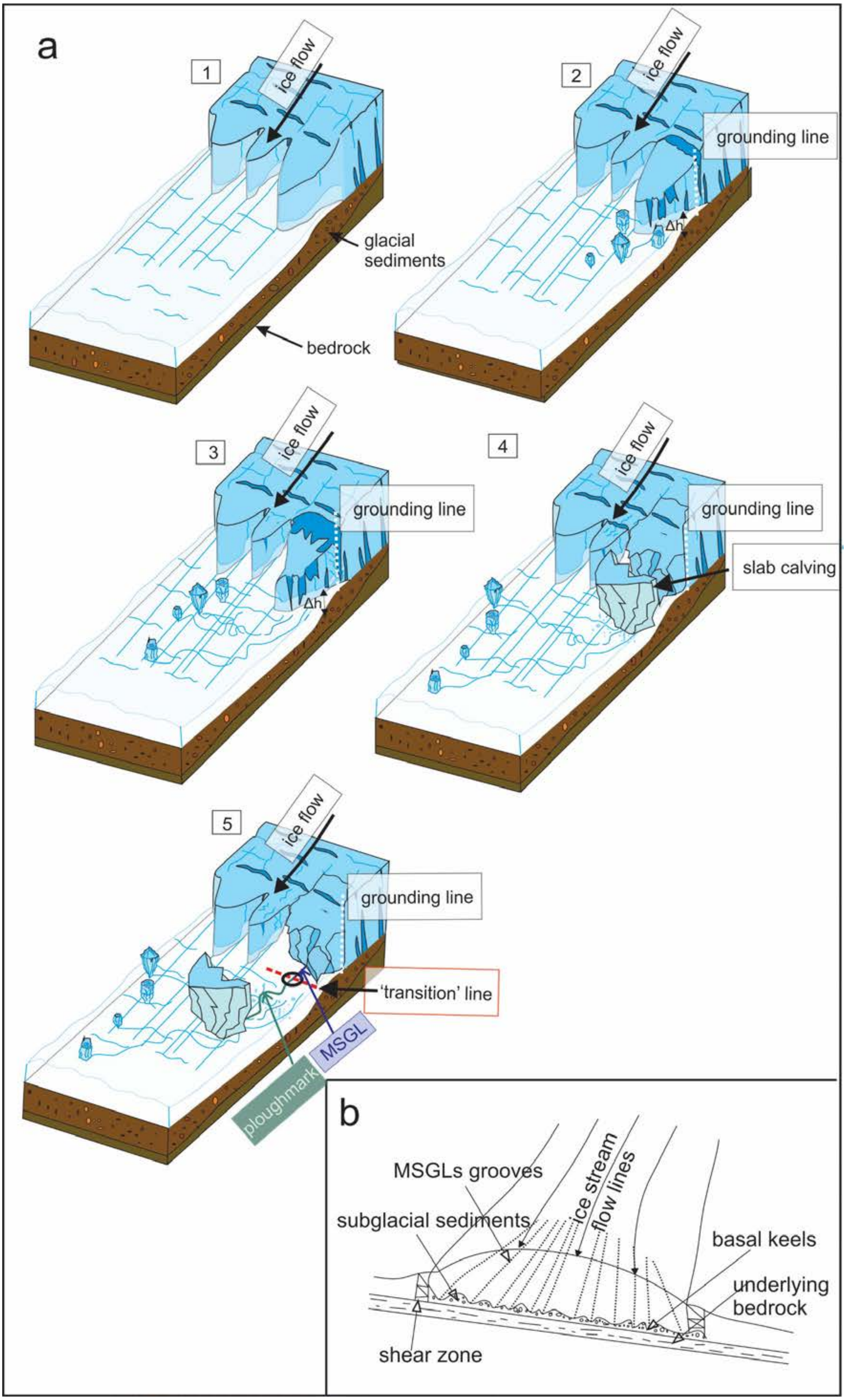

24°E
74°N
N
13
12
11
10
9
8
7
6
5
4
3
2
1
MSGLs (grooves)
measurement points
inferred ice margin
('transition zone')
MSGL/chart designation
depth
m
480
430
0
km
10

829



slope gradient
1
8%
2
4.5%
3
10%
4
3%
5
11%
6
10%
7
3%
8
10%
9
12%
10
3%
11
17%
12
26%
13
3%
Groove depth [m]
Groove depth [m]
-25 -15 -5 0 5 15 25 35 45
Proglacial [km]
Subglacial [km]
inferred grounding line

831 
a
N
[m]
420
440
460
480
1
2
3
4
5
6
7
8
ice flow
0
km
10
b
350
300
250
200
150
100
50
0
Groove width [m]
8
7
6
5
4
3
2
1
Transect number (see main panel)
MSGL1
MSGL2
MSGL3
MSGL4
MSGL5
MSGL6
MSGL7
MSGL8
MSGL9
MSGL10
MSGL11
MSGL12
MSGL13


a
1
ice flow
glacial sediments
bedrock
2
ice flow
grounding line
Δh
3
ice flow
grounding line
Δh
4
ice flow
grounding line
slab calving
5
ice flow
grounding line
'transition' line
MSGL
ploughmark
b
MSGLs grooves
ice stream flow lines
subglacial sediments
basal keels
underlying bedrock
shear zone

832