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What controls the location of ice streams?

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ABSTRACT

Ice streams influence ice sheet mass balance and stability but key aspects of their behaviour remain poorly understood. This paper reviews and discusses one very important aspect: what controls their location in an ice sheet? Seven potential controls on ice stream location are identified from the literature: topographic focusing, topographic steps, macro-scale bed roughness, calving margins, subglacial geology, geothermal heat flux and subglacial meltwater routing. For each control, the theoretical basis for its link to rapid ice flow is introduced, followed by discussion of the evidence of its influence on the location of both contemporary and palaeo-ice streams. Based on this new synthesis, topographic focusing, subglacial geology, meltwater routing and calving margins appear to be most commonly associated with fast ice flow. It is clear that rather than a single control, however, there exist a number of potential controls of varying influence. We propose a hierarchy of factors, with those occurring at the top of the hierarchy exerting a stronger influence on ice stream location, and where present beneath an ice sheet, are very likely to be associated with fast flow. Those factors occurring lower down the hierarchy are less commonly associated with ice streaming but appear to be influential in the absence of more common controls. In such a hierarchy topographic focusing in the presence of a calving margin is the primary control. In the absence of this, ice streams will preferentially occur in areas with favourable subglacial meltwater routing and subglacial geology. In the absence of these, bed roughness, geothermal heat flux and topographic steps may promote ice streaming. Significantly, the primary controls on a given ice stream location are likely to influence its spatial and temporal dynamics. Ice streams governed by the presence of meltwater routing and/or calving processes might exhibit more variable behaviour because these controls can vary over relatively short time-scales compared to controls that vary over longer time-scales, e.g. geothermal heat flux, subglacial roughness, geology and topography. Identifying the controls on ice stream location is therefore of paramount importance when understanding ice stream longevity and their past and future activity.

Contents

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1. Introduction

Ice streams dominate mass loss from ice sheets but the factors that influence their location can be difficult to ascertain, and a number of possible factors have been identified. It is known that they are highly variable both spatially and temporally, with numerous examples of ice streams switching on and off, accelerating, decelerating, migrating and changing flow direction (e.g. Conway et al., 2002; Joughin et al., 2004a; Joughin et al., 2005; Catania et al., 2006; Dowdeswell et al., 2006; Van der Veen et al., 2007; Stokes et al., 2009; Ó Cofaigh et al., 2010). The difficulty of 'dating' palaeo-ice stream activity and the short time-scales of modern observational data often do not reveal if these fluctuations reflect instability, and are a precursor to rapid deglaciation, or whether they represent minor variability in a longer-term trend or even that of an ice sheet in equilibrium. This makes it extremely difficult to evaluate the response of the Greenland and Antarctic Ice Sheets to future climatic changes and their likely impact on global sea level (Alley et al., 2005; Vaughan and Arthern, 2007). To improve understanding of ice stream behaviour and longevity, one question of fundamental importance is: what controls their location in an ice sheet?

Due to thermomechanical feedbacks, it appears that an ice sheet will inherently stream (Clarke et al., 1977). Numerical modelling experiments reveal that, on a uniform bed, ice stream location will tend towards uniformity, with a radial self-organised flow regime (Fig. 1a). This has been demonstrated in modelling (Payne and Dongelmans, 1997; Hulton and Mineter, 2000; Boulton et al., 2003; Hindmarsh, 2009), but observations of contemporary ice sheets indicate non-regularity in ice streaming which indicates that there are confounding controls on their location (Fig. 1b). Identifying the factors which determine why ice streams are located where they are is likely to advance our understanding of their mode of operation, especially over long time-scales, and lead to an improved understanding and prediction of ice sheet behaviour.

In this paper, we identify seven potential controls on ice stream location that have been postulated in the literature: topographic focusing, topographic steps, topographic roughness, calving margin, subglacial geology, geothermal heat flux and subglacial meltwater routing (conceptualised in Fig. 2). Our aim is to synthesise the available information on each of these hypothesised controls and evaluate their likely importance in determining ice stream location. It is important to state at the outset (although it is addressed in more detail in the discussion), that it can be difficult to assess causality when investigating controls on ice stream location. This is because ice stream flow modifies the bed and so it is sometimes difficult to assess whether a hypothesised association is a cause or effect of ice stream activity. A good example of this is the investigation of bed roughness as a control on ice stream location (e.g. Siegert et al., 2004). Does an observation of smooth ice stream beds in comparison to adjacent non-streaming areas indicate that ice streams are located preferentially in areas of low bed roughness or that, over time, ice streams smooth their beds to a greater degree than slower flowing areas of the ice sheet? Given this problem, it is important to consider carefully the spatial and temporal scales at which ice stream processes occur, and to consider as large a dataset of ice streams as possible when investigating their potential controls.

2. Background

Following the early pioneering studies that identified ice streams in Antarctica (Robin et al., 1970; Rose, 1979), there was a major research focus on their activity in the 1980s and it was not long before McIntyre (1985) noted a link between ice streams and troughs in subglacial topography. This correlation provided an intuitive explanation for the generation of rapid ice flow and emerged as the dominant paradigm. However, detailed investigation of the Siple Coast Ice Streams in West Antarctica (formerly A, B, C, D and E; now named Mercer, Whillans, Kamb, Bindschadler and MacAyeal, respectively), challenged this paradigm because they were found to operate in extremely shallow troughs that do not focus ice or significantly influence their lateral margin location (e.g. Shabtaie and Bentley, 1987). This demonstrated that topographic focusing was not a necessary condition for ice streaming, and the challenge to explain the location of the Siple Coast ice streams fuelled further research.

A major advance came with the identification of a metres-thick, saturated till layer, inferred to be deforming, beneath Whillans Ice Stream (Alley et al., 1986; Blankenship et al., 1986; Alley et al., 1987b; Blankenship et al., 1987). It was suggested that streaming ice flow could be promoted by deformation of the subglacial till layer and this was widely heralded as the explanation for streaming activity in the absence of topographic control (e.g. Anandakrishnan et al., 1998; Bell et al., 1998), although the precise flow mechanism (basal sliding versus subglacial till deformation) remains open to debate (e.g. Engelhardt and Kamb, 1997). However, with increasing awareness of the location of palaeo-ice streams (e.g. Stokes and Clark, 1999, 2001), a subglacial geological control on ice stream location has been found lacking in some circumstances (e.g. Piotrowski et al., 2001; Stokes and Clark, 2003a), with further support from numerical modelling studies (e.g. Payne and Dongelmans, 1997). This has led to the suggestion that other mechanisms may be important in controlling ice stream location, such as macro-scale bed roughness (e.g. Siegert et al., 2004), the distribution of subglacial meltwater (e.g. Hulbe and Fahnestock, 2004), variations in geothermal heat flux (e.g. Fahnestock et al., 2001) and marine (e.g. Shaw, 2003) or lacustrine calving margins (e.g. Stokes and Clark, 2004).

We now identify and review seven potential controls on ice stream location that have been postulated in the literature and synthesise

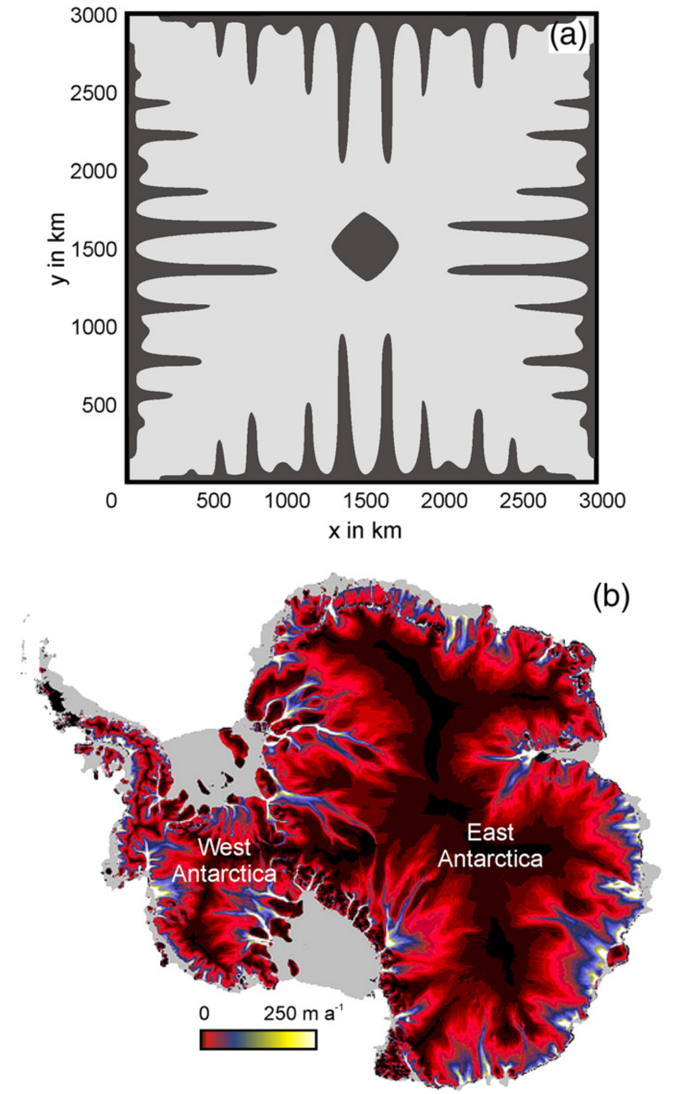

Fig. 1. (a) An idealised ice sheet model showing simulated variations in basal temperature (modified from Payne and Dongelmans, 1997). A distinctive spatial patterning is seen with widespread areas of cold-based ice (grey) and, within this, fingers of warm-based ice (black) developing at regular intervals along the margin. This led to the suggestion that, due to thermomechanical feedbacks, an ice sheet resting on a uniform bed will inherently stream, and that the ice streams will self-organise to form a radial pattern around the ice sheet margin. (b) Contemporary ice sheets, however, do not show such self-regulation of their basal thermal regime, as illustrated by this map of balance velocities of the Antarctic Ice Sheet (modified from Bamber et al., 2000), suggesting that their are confounding controls on their location.

their theoretical basis and empirical evidence from both contemporary and palaeo-ice streams. The theoretical basis for each proposed control is introduced, followed by a review of specific examples of ice streams whose location is hypothesised to be controlled by this factor. The relative importance of each potential control will then be discussed, before introducing a proposed hierarchy of controls which may influence ice stream location within an ice sheet.

3. Topographic focusing of ice streams

3.1. Theory

Several processes operate to initiate ice streams in deep topographic troughs. Firstly, focusing of ice through a constriction requires an increase in velocity to maintain a constant discharge through a smaller cross-sectional area. This mechanism is particularly effective when ice is channelled through topographic troughs. Secondly, thicker ice in topographic lows generates more heat through frictional heating, which enhances basal meltwater production, lubricating the bed and promoting fast flow (Paterson, 1994). Given the dependence of ice viscosity on temperature, an increase in heat production will also promote greater deformation, further enhancing fast flow (Clarke et al., 1977). Thicker ice provides greater insulation, again increasing basal temperatures and promoting higher basal melt rates and ice deformation. Once initiated, thermomechanical feedbacks will sustain rapid ice flow. Finally, thicker ice also allows the pressure melting point to be reached earlier than in thinner ice, making it more likely that fast flow is initiated in troughs.

Numerical modelling also suggests that such thermomechanical feedbacks are sufficient to initiate ice streaming and enhanced flow velocities (ice streams) are routinely generated in model experiments that incorporate topographic troughs (Boulton et al., 2003; Siegert and Dowdeswell, 2004). Hindmarsh (2001) used modelling to specifically examine the influence of flow-parallel and flow-perpendicular perturbations in basal topography and found maximum heating, and thus flow enhancement, in topographic lows of flow parallel troughs.

3.2. Evidence

The efficacy of topographic focusing in generating fast flow is demonstrated by the common observation of palaeo-ice streams which operated in subglacial troughs or basins (e.g. Denton and Hughes, 1981; Andrews and MacLean, 2003; Ottesen et al., 2005). Contemporary outlet glaciers of the Greenland Ice Sheet also provide a number of examples of topographic focusing. The classic example being Jakobshavn Isbræ in West Greenland, which flows through a deep (in excess of 2000 m) subglacial trough, achieving velocities of up to 12.6 km a^{-1} at its calving margin (Truffer and Echelmeyer, 2003; Joughin et al., 2004a). High basal shear stresses of 200–300 k Pa are generated in this deep subglacial trough, yielding very high rates of internal ice deformation close to the bed (Clarke and Echelmeyer, 1996).

Mapping of palaeo-ice streams has demonstrated that topographically constrained ice streams were common during the last glacial cycle, for example, along the western and northern margin of the Scandinavian Ice Sheet (Sejrup et al., 2003; Ottesen et al., 2005; Ottesen et al., 2008; Winsborrow et al., 2010), and the northern and eastern margins of the Laurentide Ice Sheet (Andrews and MacLean, 2003; Winsborrow et al., 2004; Shaw et al., 2006; De Angelis and Kleman, 2007; Stokes et al., 2009). These topographically constrained ice streams were often very large, representing the major drainage conduits. As such, they strongly influenced both ice sheet dynamics and ocean circulation, e.g. Hudson Strait Ice Stream (MacAyeal, 1993; Andrews and MacLean, 2003) M'Clure Strait Ice Stream (Stokes et al., 2005) in the Laurentide Ice Sheet, and the Norwegian Channel Ice Stream in the Fennoscandian Ice Sheet (Sejrup et al., 2003; Nygård et al., 2007).

Distinctions have been made in the literature between topographic and non-topographic or 'pure' ice streams (e.g. Bentley, 1987; Stokes and Clark, 1999; Truffer and Echelmeyer, 2003). Despite having similar velocities, they often have important differences in terms of their behaviour (see review in Bennett, 2003), the most significant being that pure ice streams show greater spatial and temporal variability. However, the view that topographic ice streams are more stable and pure ice streams are more variable may be too simplified. For example, satellite radar interferometry has revealed that the tributaries of the 'pure' Siple Coast Ice Streams show a close coincidence with subglacial topography, perhaps indicating an upstream topographic control (Joughin et al., 1999; Bamber et al., 2000). Whilst the supposedly stable topographic ice stream Jakobshavn Isbræ has shown very large velocity fluctuations, with a two-fold increase in flow velocity between 1992 and 2003 (Joughin et al., 2004a). As such, both pure and topographic ice streams clearly

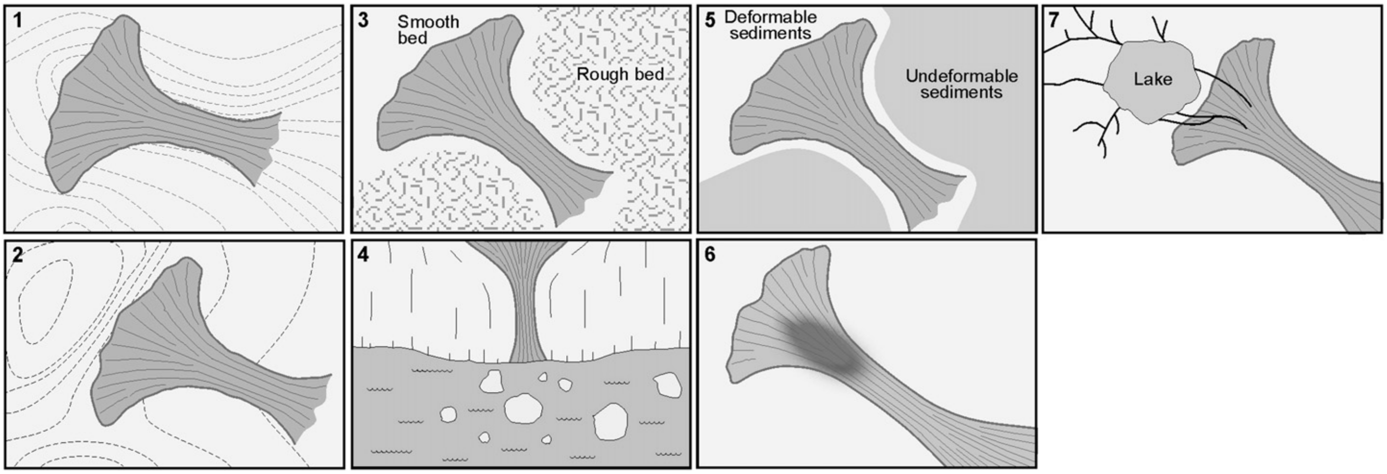

Fig. 2. Potential controls on ice stream location identified in the literature: (1) topographic focusing, (2) topographic steps, (3) macro-scale topographic roughness, (4) calving margins, (5) subglacial geology, (6) geothermal heat flux and (7) subglacial meltwater routing.

experience oscillations in their flow velocity (whether this counts as instability is a moot point), but unlike pure ice streams, topographically constrained ice streams are clearly anchored in location and unable to migrate laterally over short time-scales.

Clearly there is a long association between topographic troughs and ice streaming, and the number of ice streams operating in topographic troughs suggests that topographic focusing is an important control on ice stream location. The operation of ice streams in the absence of topographic constraint, however, indicates that it is not a necessary condition for ice streaming.

4. Topographic steps

4.1. Theory

In addition to large scale ice-directional focusing, smaller topographic variations, such as steps (steep jumps in subglacial topography of the order 10^2 m), influence ice flow and have been suggested to control ice stream location (e.g. McIntyre, 1985). Again, this results from the strain-heating feedback. An initial increase in temperature is triggered as ice flowing over a step is forced to accelerate. This causes a decrease in ice viscosity and, hence, ice will deform more readily and ice velocities will increase (McIntyre, 1985). This further increases ice temperatures, setting up a positive thermo-mechanical feedback loop.

Numerical modelling supports the proposed relationship between topographic steps and acceleration of ice flow. Pohjola and Hedfors (2003) modelled the flow of two outlet glaciers down escarpments in Dronning Maud Land, East Antarctica (Fig. 3). If strain-heating feedbacks were not included in their model, velocities downstream of the escarpment were significantly underestimated. If, on the other hand, strain-heating feedbacks were included, the observed velocity patterns were successfully reproduced. It was concluded that increased strain-heating as the ice flowed over the topographic step was responsible for the acceleration of flow of these glaciers. Although these model experiments highlight the importance of strain-heating in ice flow acceleration, the effectiveness of this mechanism at initiating and maintaining fast flow remains unclear because several factors may reduce its effectiveness over time. For example, as the ice warms and accelerates, melting occurs at the base. This melting requires latent heat which limits the warming effect and also reduces frictional resistance to sliding, thereby reducing driving stresses (Paterson, 1994). Furthermore the accelerating ice may cause thinning at the ice sheet surface, reducing its insulating potential. Over longer time-scales, the glacier may also erode and smooth out topographic variations such as steps (e.g. through plucking of the lee-side of a topographic step).

4.2. Evidence

Topographic steps were first noted by McIntyre (1985) who observed ice velocity increases downstream of topographic steps in Antarctic outlet glaciers. On Byrd Glacier, for example, McIntyre noted a five-fold increase in ice velocity 8 km downstream of a 150 m high topographic step, which increased to eight-fold a further 55 km downstream of the step. Other Antarctic outlet glaciers where increased ice velocity coincides with topographic steps include Frost Glacier, Ninnis Glacier, Thwaites Glacier and Rutford Ice Stream (McIntyre, 1985; Bentley, 1987; Doake et al., 2001). Interestingly, no topographic steps have been reported in the onset areas of palaeo-ice

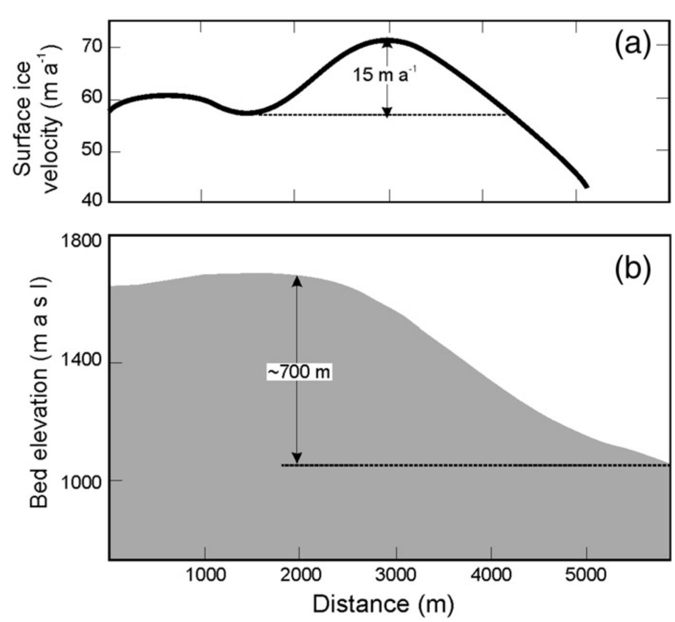

Fig. 3. The influence of a topographic step on ice surface velocities (modified from Pohjola and Hedfors, 2003). (a) Surface ice velocity and (b) subglacial topography along a longitudinal transect in the upstream section of Bonnevie–Svendsenbreen, East Antarctica. The bed topography drops ~700 m in elevation over ~4 km, and this is broadly coincident with an increase in ice surface velocity from ~55 m a^{-1} to ~70 m a^{-1}.

streams and little research on this potential control has been carried out in formerly glaciated areas, despite the availability of high resolution topographic data of palaeo-ice sheets beds, compared to their modern-day counterparts.

5. Macro-scale bed roughness

5.1. Theory

Localised changes in the roughness of an ice sheet bed have been suggested to exert a control on ice stream location (e.g. Siegert et al., 2004). Theories regarding the flow of ice around small (<10 m wavelength) bedrock obstacles are well-established (Weertman, 1957, 1964; Nye, 1969; Kamb, 1970; Weertman, 1972), but surprisingly little analysis has been carried out at the macro-scale (~1–100 km). This scale is of particular interest, however, as it includes sub-ice stream scale roughness elements and subglacial bedforms.

Macro-scale bed roughness on an ice sheet bed is a consequence of the direction of ice flow, ice dynamics, lithology and geological structure and influences frictional resistance to ice flow and basal lubrication (Taylor et al., 2004). A bedrock bump will offer resistance to ice flow in two ways. The first is due to form drag: the resistance exerted by an obstacle as the ice flows around it. The second is due to the thin (or absence of) till that is often associated with localised topographic high-points, and can cause a higher frictional resistance to ice flow. Both of these processes decrease ice velocities in areas of high bed roughness.

Compared to other potential controls, macro-scale bed roughness has traditionally been overlooked as an influence on ice stream dynamics, largely because accurate topographic data from beneath contemporary ice sheets is difficult to obtain. However, geomorphological observations on palaeo-ice stream beds have frequently indicated a preference for smooth, flow-parallel orientated bedforms (e.g. mega-scale glacial lineations: Stokes and Clark, 1999; Canals et al., 2000; Evans et al., 2008) and these have recently been identified under a West Antarctic ice stream (King et al., 2009). Flow transverse bedforms (i.e. ribbed moraines) are rare on ice stream beds (cf. Stokes et al., 2007), but where they have been observed, their presence has been linked to localised areas of increased frictional resistance in ice stream onsets zones (Dyke and Morris, 1988) or the development of sticky spots during ice stream shut-down (Stokes and Clark, 2003b).

Numerical models indicate that strain-heating feedback loops operate to create spatial differences in the distribution of heat within ice flowing over an uneven bed, which are manifest as spatial variations in ice velocity (Hindmarsh, 2001; Schoof, 2004). In modelling the flow of streaming ice over a rough bed (an idealised drumlin field with roughness of a single wavelength, roughly equivalent to ice thickness), Schoof (2004) observed the development of spatial variability in basal sliding and ice velocity, which resulted in surges in ice stream velocity. It was predicted that the inclusion of more realistic bed topography (roughness at a variety of wavelengths) would trigger large enough velocity oscillations to cause ice stream shut-down during slow flow, implying a strong influence of macro-scale bed roughness on ice stream dynamics.

Modelling has also been used to investigate the influence of macro-scale bed roughness with respect to its orientation to ice flow direction (Hindmarsh, 2001). Roughness parallel to flow preferentially channels ice through topographic lows, leading to maximum heat generation in these lows and maximum ice velocity. On adjacent topographic highs, the ice thins, cools and slows down. Heat generation becomes increasingly focused in topographic lows, providing a mechanism for the initiation of ice streams in these locations. The opposite is true of flow-transverse topographic roughness, with maximum heating on bedrock highs due to the generation of high shear stresses. As heating continues, shear stress reduces on the bedrock highs, and the warming ceases. Unlike flow parallel roughness, transverse roughness does not lead to the development of large spatial variations in ice velocity.

5.2. Evidence

As noted above, assessment of the influence of macro-scale bed roughness on ice stream location has been limited, largely due to the inaccessibility of contemporary ice sheet beds. However, recent studies have calculated bed roughness from radio-echo sounding data and these have suggested that it may influence ice dynamics and the location of streaming flow (Siegert et al., 2004; Taylor et al., 2004; Siegert et al., 2005; Rippin et al., 2006; Bingham and Siegert, 2007). These studies have characterised macro-scale bed roughness using Fast Fourier Transforms of the ice sheet bed as a proxy for the wavelength of subglacial topographic variation (Taylor et al., 2004). It has so far been used beneath several Antarctic ice streams: the Siple Coast Ice Streams (Siegert et al., 2004; Bingham and Siegert, 2007), Slessor Glacier (Rippin et al., 2006) and Institute and Möller Ice Streams (Bingham and Siegert, 2007) as well as parts of southern and central East Antarctica (Siegert et al., 2005).

An example of the macro-scale roughness calculated from beneath the Siple Coast Ice Streams is shown in Fig. 4 (Siegert et al., 2004; Bingham and Siegert, 2007). Clear spatial variations in bed roughness are seen, with low roughness in actively streaming areas, and high roughness in non-streaming areas. A downstream decrease in roughness is also noted along individual ice streams and is attributed to the presence of unconsolidated, deformable, subglacial sediments further downstream, which may be masking topographic roughness elements. The adjacent rougher areas are considered to reflect the existence of preglacial topography. Siegert et al. (2004) note a particular decline in short wavelength roughness (5–10 km) beneath the ice streams, suggesting that this offers the greatest resistance to ice flow and is, therefore, preferentially removed by ice stream erosion. Based on these findings, the authors suggest that "bed roughness [....] may play a part in defining the general region of ice streaming" (Siegert et al., 2004, p.1595) and that roughness may exert a stronger control on the location of these ice streams than does subglacial geology.

A similar pattern of roughness variation is seen beneath Möller and Institute Ice Streams, West Antarctica (Bingham and Siegert, 2007), with roughness increasing away from the areas of active streaming. They propose that low roughness encourages fast flow and is indicative of a thick subglacial deforming sediment layer. Marshall et al. (1996) also investigated roughness of the Laurentide Ice Sheet bed using cell-based measurements of the range in elevation from a DEM. However, the coarse resolution and a lack of knowledge regarding palaeo-ice stream locations, at that time, did not permit detailed investigation of the roughness of their beds. As such, no links were made between ice velocity and bed roughness. However, for some palaeo-ice streams identified in Alberta, Canada, it has been noted that the ice stream tracks are remarkably smooth in relation to the surrounding terrain (Evans et al., 2008).

All these studies highlight the potentially important role of subglacial roughness but there are difficulties in assessing whether ice streaming preferentially occurs in areas of low bed roughness, or whether ice streaming preferentially smoothes the bed.

6. Marine or lacustrine calving margins

6.1. Theory

A calving margin is an efficient way of both removing ice and drawing down ice from further inland, a process which Hughes (1992) termed 'ice stream pulling power'. As ice is lost at a calving margin, the ice surface profile can lower, facilitating the capture of increasing volumes of ice from the catchment. In addition to this, subglacial water pressures may increase close to the site of calving, reducing basal shear stresses and increasing ice velocity upstream of the calving margin. These two processes set up a positive feedback system whereby the

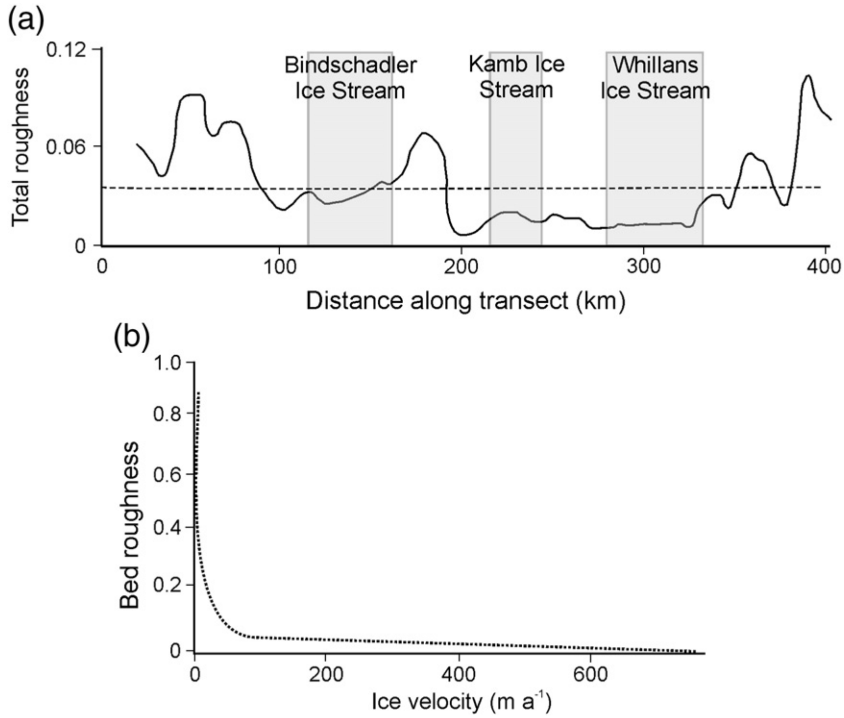

Fig. 4. Macro-scale bed roughness of the Siple Coast Ice Streams estimated from radio-echo sounding data, modified from Bingham and Siegert (2007) and Siegert et al. (2004). Roughness is defined as the integral of the forward fast Fourier transform of the basal reflector and panel (a) shows bed roughness variations across Bindschadler, Kamb and Whillans Ice Streams, West Antarctica, and intervening non-streaming areas (Siegert et al., 2004). Mean roughness is indicated by the black dashed line. Ice stream beds typically display lower than average total roughness, whilst non-streaming areas display higher than average roughness. (b) Bed roughness versus satellite derived ice velocity for the catchment of Whillans, Mercer, Kamb, Bindschadler and MacAyeal Ice Streams, West Antarctica (Bingham and Siegert, 2007). Low bed roughness is associated with fast ice velocities whilst high bed roughness is associated with slow ice velocities.

increasing ice velocities trigger increasing heat generation and meltwater production, which in turn further promote fast flow.

It is also thought that ice shelves or ice tongues may buttress ice streams and outlet glaciers against faster flow (Thomas, 1979), although the precise influence of this process is debated (Hindmarsh and Le Meur, 2001). The removal of such buttressing and the subsequent increase in calving flux has been suggested as a means of accelerating ice stream flow and has been proposed as a mechanism for major episodes of instability in palaeo-ice sheets (e.g. Hughes et al., 1977; Hulbe et al., 2004; Bradwell et al., 2008). Recent observations support such a link, with analysis of satellite images and airborne surveys indicating that five of the six major tributaries which flowed into the Larsen Ice Shelf experienced significant changes in their flow dynamics following its partial collapse (De Angelis and Skvarca, 2003). For example, Sjögren Glacier advanced about 1.25 km, and its flow velocity doubled from 1.8 m day^{-1} to 2.4 m day^{-1} over a 2 year period. Interestingly, ice flow acceleration was only observed on the fast-flowing tributaries, not intervening slower moving areas of ice; implying that the basal and thermal conditions beneath fast-flowing sections are more sensitive to removal of buttressing (De Angelis and Skvarca, 2003).

6.2. Evidence

Calving is an extremely important means of discharging ice from contemporary ice sheets, accounting for 90% of the mass lost from Antarctica, and ~50% from Greenland (Hooke, 2005). All contemporary ice streams are marine-terminating, discharging ice by calving into open water or via ice shelves. The efficiency of this process is demonstrated by Jakobshavn Isbræ, Greenland. Recent dramatic acceleration of this ice stream has been attributed to increased calving following loss of its floating ice tongue (Fig. 5). Between 1985 and 2003, ice velocity increased from 6700 m a^{-1} to 12600 m a^{-1}, associated with a suggested near doubling of calving rate from 26.5 km^3 a^{-1} to 50 km^3 a^{-1} (Thomas et al., 2003; Joughin et al., 2004a; Joughin et al., 2008).

The presence of a lacustrine calving margin has also been invoked to explain the initiation of the Dubawnt Lake Ice Stream, a late-glacial ice stream that operated over the north-western Canadian Shield in the Laurentide Ice Sheet. This palaeo-ice stream flowed over relatively flat, hard bedrock geology and Stokes and Clark (2004) propose that streaming was initiated by the development of calving into a series of large proglacial lakes that developed during ice margin retreat.

The potential importance of a calving margin is also supported by the numerical modelling work of Cutler et al. (2001). In their model of the southern margin of the LIS, the advance and retreat of the ice margin is seen to be significantly influenced by the distribution of proglacial lakes, through their control on rates of calving. They note that ice is able to advance through shallow lakes (~100 m), but rapid calving is initiated when ice comes into contact with deeper water, and this prevents further ice advance.

In contrast to contemporary ice streams, the palaeo-record also provides evidence for land-terminating ice streams, demonstrating that a calving margin is not a necessary condition for ice streaming. The southern margin of the Laurentide Ice Sheet had several examples (e.g. Patterson, 1998), with ice discharge achieved by the development of a large splayed terminus which may extend beyond the ice margin of non-streaming areas.

7. Subglacial geology

7.1. Theory

Ice flows through a combination of internal deformation, basal sliding and subglacial sediment deformation (Paterson, 1994). Streaming velocities are not usually achieved through ice deformation alone, but often require a lubricating basal layer of either meltwater or saturated sediment. Both processes are enhanced by pressurised water at the ice-bed interface, which can be influenced by subglacial geology. Subglacial geology will determine the amount (i.e. thickness)

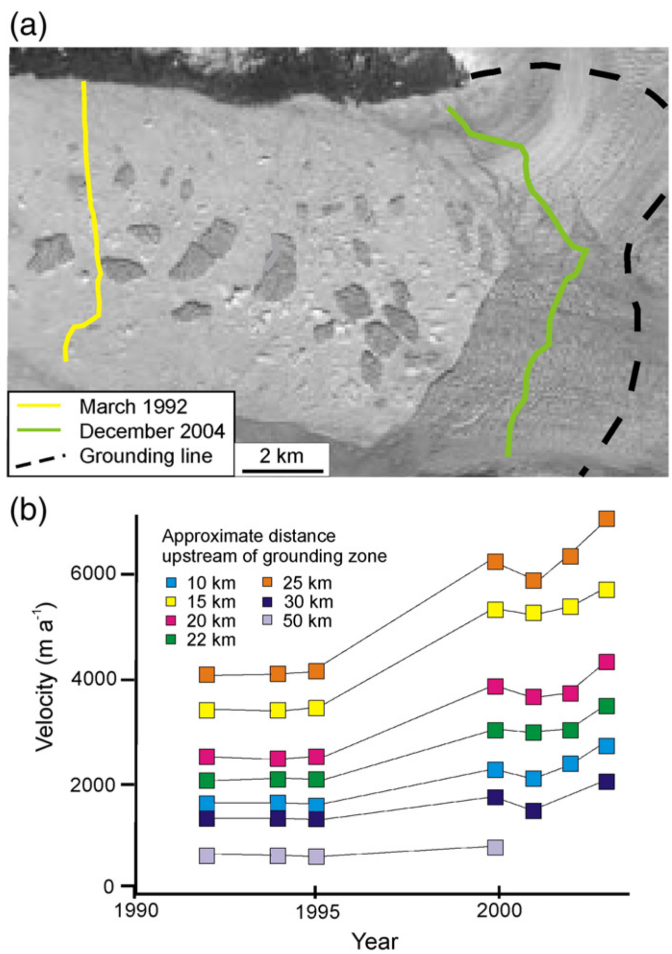

Fig. 5. (a) Landsat image from May 2003 showing the ice tongue of Jakobshavn Isbræ, Greenland and its collapse from March 1992 to December 2004 (modified from Alley et al., 2005). (b) Ice stream velocity at several points along the main trunk of Jakobshavn Isbræ between 1992 and 2003 (Joughin et al., 2004; Joughin et al., 2008), indicating that the collapse of the ice tongue was coincident with rapid acceleration of the ice stream.

and character (i.e. grain size, porosity) of subglacial tills, and the ease at which these will saturate (Alley, 2000). A basal layer of soft sediments may enhance ice flow by: i) masking bed roughness and thus reducing basal resistance to ice flow (see section 5); ii), enhancing basal sliding across the surface of sediments; and/or iii), deforming under the pressure of the overlying ice (Alley et al., 1986; Blankenship et al., 1986).

It has been hypothesised that subglacial geology exerts a primary control on ice stream location (Clark, 1994; Anandakrishnan et al., 1998; Bell et al., 1998; Blankenship et al., 2001; Studinger et al., 2001). Hard bedrock geology is not conducive to ice streaming because it is more resistant to erosion and offers greater frictional resistance to ice flow (also offering increased basal roughness; see section 5) and any till produced tends to be coarse-grained, highly permeable and discontinuous (cf. Clark, 1994). It has a low potential to deform and is inefficient at masking bed roughness. Locations with sedimentary bedrock or continental shelf and fjord settings, however, are considered most likely to host ice streams because of the tendency towards fine-grained, thick and continuous subglacial till cover (Clark, 1994; Tulaczyk et al., 1998; Heroy and Anderson, 2005).

7.2. Evidence

Interest in the potential contribution of subglacial sediments to ice motion increased with the discovery of lubricating sediments at the bed of Whillans Ice Stream, West Antarctica (Alley et al., 1986; Blankenship et al., 1986). Seismic and borehole investigation (Alley et al., 1987a, b; Blankenship et al., 1987; Rooney et al., 1987; Tulaczyk et al., 2000b) revealed that a ~5 m thick layer of unfrozen till separated the ice from the underlying bedrock. Effective pressure was estimated to be equal to the difference between the ice overburden pressure and the pore-water pressure. Later extraction of a sample of till revealed it to have a porosity of 0.4 (Engelhardt et al., 1990). This evidence was used to suggest that the sediment layer was actively deforming throughout its thickness, and that this process was responsible for the high velocities of the overlying ice stream (Alley et al., 1987b; Engelhardt et al., 1990; Tulaczyk et al., 1998). It has since been demonstrated that, in addition to subglacial sediment deformation, sliding can occur at the ice-till interface and within the till, which can further enhance flow velocities (Engelhardt and Kamb, 1998; Kamb, 2001).

Since the work on Whillans Ice Stream, similar till layers have been identified or inferred to exist beneath other Antarctic ice streams such as Rutford Ice Stream (Smith, 1997; Doake et al., 2001), Slessor Glacier (Bamber et al., 2006), Evans Ice Stream (Vaughan et al., 2003), Institute Ice Stream and Möller Ice Stream (Bingham and Siegert, 2007), leading to the suggestion that ice streams are associated with sedimentary basins. Indeed, based on aerogeophysical (Bell et al., 1998) and seismic observations (Anandakrishnan et al., 1998; Anandakrishnan and Winberry, 2004; Peters et al., 2006) there is growing evidence to suggest that the Siple Coast Ice Streams in West Antarctica overlie sedimentary basins and have a deforming subglacial sediment layer, whilst adjacent non-streaming areas overlie harder bedrock, with thin or no basal sediment layer. These observations have been used to propose that the presence of soft basal sediments is a necessary condition for fast ice flow, and that subglacial geology plays a direct role in determining the location of these ice streams (Tulaczyk et al., 1998; Studinger et al., 2001). This assertion is encapsulated in the geological template idea of Studinger et al. (2001), shown in Fig. 6. Estimating the distribution of subglacial marine sediments and sedimentary basins in the Siple Coast area of West Antarctica using aerogeophysical data, Studinger et al. (2001) conclude that a "geological template" controls the location of ice streams, and that fast flow is not possible outside the marine and sedimentary basins.

Examples of a geological influence on ice streaming also exist in the palaeo-record. Several examples are found from the Laurentide Ice Sheet, which partly overlaid soft sedimentary bedrock. One of the best documented is the M'Clintock Channel Ice Stream which drained the north-western margin of the ice sheet during its final deglaciation (Clark and Stokes, 2001; De Angelis and Kleman, 2005; Stokes et al., 2005; De Angelis, 2007). The existence of unconsolidated sediments (fine-grained tills) are suggested to have favoured the development of fast flow, and multiple cross-cutting landforms have been interpreted as the geomorphic imprint of at least three generations of ice streams operating in M'Clintock Channel during deglaciation. Each of these had its main corridor located in the shallow marine trough, but the width and exact position of each ice stream varied (De Angelis and Kleman, 2005). The final shutdown of the M'Clintock Channel Ice Stream is also suggested to have been related to the availability of subglacial sediments (Clark and Stokes, 2001). Along the western margin of the ice stream, on Victoria Island, an increase in sediment thickness is noted outside the ice stream track; whilst along the ice stream itself, till thickness decreases downstream (Clark and Stokes, 2001). Consistent with this, is a downstream increase in the proportion of exposed bedrock, reaching a maximum of 40% at the terminus, and a downstream increase in bedform density. Clark and Stokes (2001) hypothesised that the ice stream shut down due to a decrease in sediment availability. As the ice stream eroded the sediment, sufficient debris was not advected from upstream sources to prevent the exposure of bedrock. These bedrock zones offered higher frictional resistance (see section 5), acting as sticky spots and retarding ice flow.

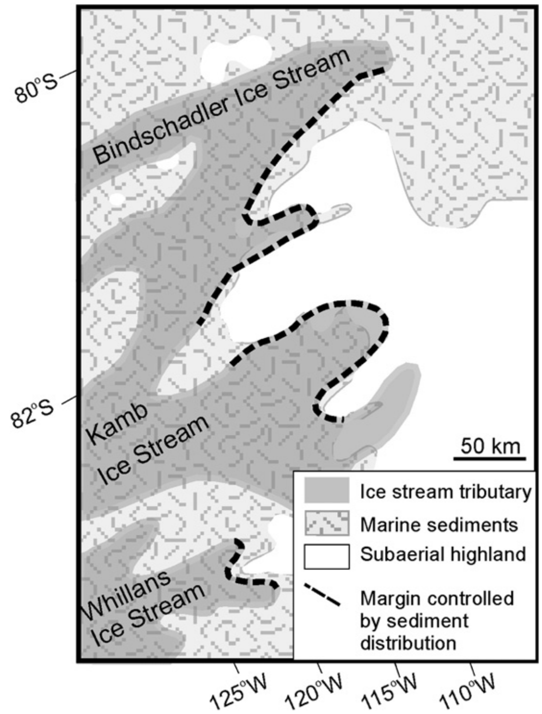

Fig. 6. A geological template for ice streaming. Based on aerogeophysical data Studinger et al. (2001) estimated the distribution of marine sediments in the Siple Coast of West Antarctica. A strong correlation is noted between the ice stream onsets and the distribution of marine sediments, with the geology suggested to act as a template, determining the extent of fast flow. Ice stream tributaries are defined based on the 25 m a^{-1} ice velocity contour from Joughin et al. (1999).

These observations provide strong support for a subglacial geological control on ice streaming, but the occurrence of non-streaming ice in areas with suitable sediments (e.g. Anandakrishnan and Winberry, 2004) and ice streams located in areas of hard bedrock (Punkari, 1980; Payne and Baldwin, 1999; Stokes and Clark, 2003; Roberts and Long, 2005), implies that soft beds are not always necessary to generate fast flow and, where present, may not be sufficient alone. Further difficulties in assessing the importance of subglacial geology to ice streaming arise from the problems in obtaining data concerning the distribution, thickness and nature of basal sediments beneath contemporary ice sheets. Estimates can be made based on borehole measurements, but given the spatial and temporal variability of the subglacial environment these may not be representative. Alternatively seismic or geophysical data may provide wider coverage, but are generally of lower resolution.

There are also concerns over the evidence from palaeo-ice sheets. Piotrowski et al. (2001) highlight the difficulties in identifying pervasively deformed sediments and argue that deforming sediments beneath past ice sheets were not as widespread as previously believed. Rather, they stress the importance of basal sliding and englacial transport, arguing that soft deforming beds occur only under exceptional circumstances, such as the Siple Coast, West Antarctica, where preglacial sediments have been recycled to produce the observed weak till.

Resolution of this issue is hampered by continuing debate over the exact mechanism by which fast flow is generated. Detailed discussion of this is beyond the scope of this paper (see Clarke, 2005 for a recent overview) but the key areas of uncertainty are: i), the relative importance of enhanced basal sliding and basal sediment deformation in contributing to fast ice flow; ii), the importance of basal water pressure to deformation and/or sliding mechanisms; and iii), the suitability of modelling basal sediment deformation using a viscous or a plastic rheology. We briefly note recent studies suggesting the presence of hybrid tills beneath Antarctic palaeo-ice streams formed through a combination of both deformation and lodgement (Dowdeswell et al., 2004; Ó Cofaigh et al., 2007), and the identification of both mega-scale glacial lineations and megablocks and rafts on bed of the Bear Island Trough Ice Stream, demonstrating the operation of both ductile and brittle deformation beneath ice streams (Andreassen et al., 2004; Winsborrow et al., 2010). These offer a taste of the likely complexity of the sub-ice stream environment, and theories regarding the role of subglacial sediments in the generation of fast flow need to be able to account for this variability.

8. Geothermal heat flux

8.1. Theory

The fast flow of most ice streams is dependent on effective basal lubrication, which is influenced by the production and routing of subglacial meltwater. The routing of meltwater is discussed in section 9, whilst here we consider its production. Subglacial melt rates are determined by viscous heat generation due to vertical shear and frictional resistance at the base of the ice, and geothermal heat flux. Considering the second of these, non-uniform geothermal heat flux beneath an ice sheet will influence basal temperature, the distribution of warm- and cold-based ice and the production of subglacial meltwater (Jarosch and Gudmundsson, 2007). These, in turn, affect basal sliding and subglacial hydrology, the deformation of soft basal sediments, and rates of erosion. Where heat flux is high, basal melt production will be enhanced and basal sliding and/or the deformation of saturated soft sediments will occur more readily (Blankenship et al., 1993). Furthermore, elevated geothermal heat flux may raise the temperature of basal ice to the pressure melting point in otherwise frozen areas. The presence of subglacial lakes beneath the ice sheets which covered Grimsvötn and Katla volcanoes in Iceland has long been attributed to the high geothermal heat flux (Thorarinsson, 1953, 1957; Björnsson, 1974, 1975).

A strong link between geothermal heat flux and basal temperature is indicated by the analytical modelling of Tulaczyk et al. (2000a). In this study, field data are used to model the evolution of Whillans Ice Stream, West Antarctica, focusing particularly on till properties and basal melt rates. They note a fundamental dependence of basal thermal regime on the geothermal heat flux, with both basal melting and basal freezing possible, depending on the value of the geothermal heat flux value. A similar scenario is predicted by the numerical modelling of Greve and Hutter (1995), who showed that significant differences in ice surface elevation, basal thermal regime, and total ice volume of the Greenland Ice Sheet are triggered by a reduction in geothermal heat from 29.4 to 54 m W m^{-2}. Particularly important is the influence on ice sheet basal thermal regime, with 51% of the ice sheet at the pressure melting point at the higher geothermal heat flux value, whilst only 33% at the lower heat flux. This is supported by modelling of the Fennoscandian Ice Sheet where an increase in mean geothermal heat flux from 42 to 49 m W m^{-2} leads to a 1.4 times greater total basal melt production over the Last Glacial Maximum (Naslund et al., 2005).

8.2. Evidence

Variations in geothermal heat flux have been proposed to explain the location of the onset of the Siple Coast Ice Streams, West Antarctica (Blankenship et al., 1993). In this area, the lithosphere is characterised by a thin and relatively hot crust and aerogeophysical surveys have identified a distinct depression in the ice surface which is underlain by a peak in subglacial topography associated with a unique magnetic signature (Fig. 7). These are interpreted as abundant basalts, consistent with a recently active volcano and with an estimated geothermal high flux of 10 000–25 000 mW m^{-2}

(Blankenship et al., 1993; Behrendt et al., 1994). Based on these data, it has been suggested that spatial variations in geothermal heat flux determine the supply of basal meltwater which is available to saturate the subglacial sediments and hence permit the fast flow of the ice streams. However, the aerogeophysical data on which these interpretations are based is not able to constrain the age of these basalts, and if older than Cenozoic, they are unlikely to be associated with high geothermal heat flux values. To test this, Vogel et al. (2006) obtained subglacial sediment samples from the West Antarctic Ice Sheet and concluded that they did not indicate the presence of large mafic exposure of late Cenozoic age. Instead, they found that mafic rocks were only present in 1 of the 5 sampling locations (Byrd Station), and that these were Mesozoic to Cambrian in age. However, they did point out the potential for individual subglacial volcanic centres, such as Mt. Casertz (identified as a potential geothermal heat source by Blankenship et al., 1993), to locally increase basal melt rates and influence ice dynamics.

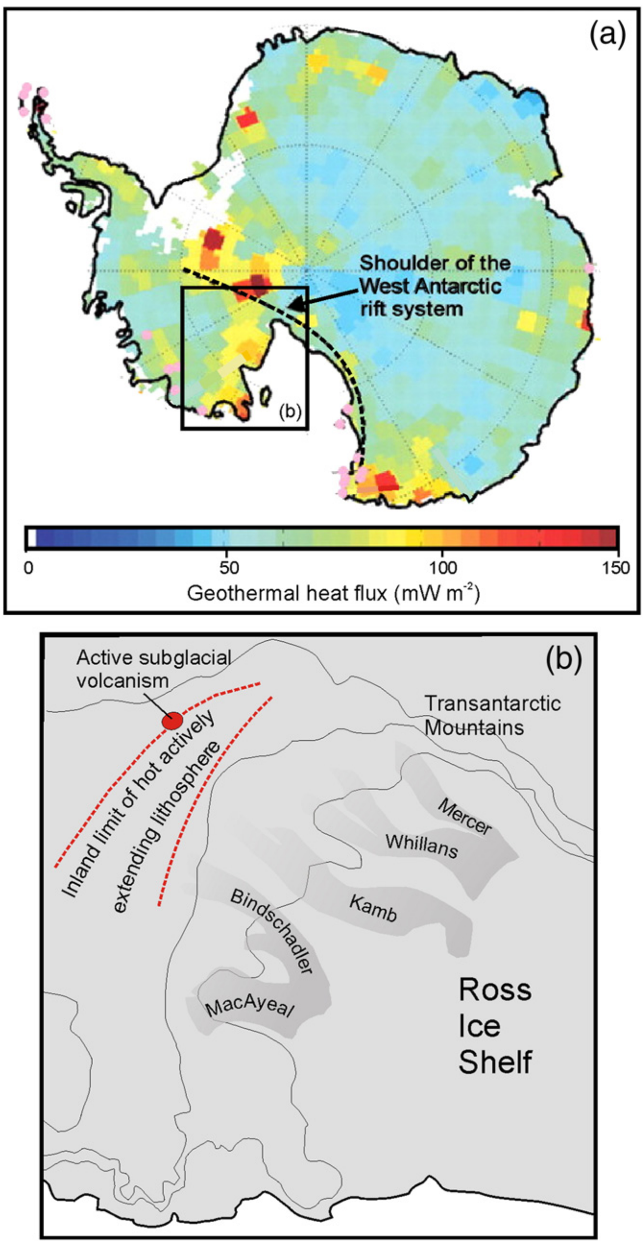

Fig. 7. (a) A geothermal heat flux map of Antarctic based on interpretation of magnetic satellite data (Maule et al., 2005). Heat flux values show a wide range, with particularly high values associated with the West Antarctic rift system and around the Siple Coast, where several ice streams currently operate. (b) Part of West Antarctic Ice Sheet around the Siple Coast Ice Streams showing the location of active subglacial volcanism and the inland extent of hot extending lithosphere, both of which are indicative of high geothermal high flux (modified from Blankenship et al., 1993).

Maule et al. (2005) estimated geothermal heat flux across Antarctica using satellite-derived magnetic data, based on the assumption that the magnetic properties of rocks vary with temperature. They noted considerable variations in heat flux, as seen in Fig. 7, with values ranging from 40 to 185 mWm^{-2}. Interestingly, high heat flux values (exceeding 100 mW m^{-2}) are found in the Siple Coast region, where several ice streams operate. Validation of this map is problematic given the scarcity of direct measurements, but borehole data from Siple Dome (between Kamb and Bindschadler Ice Streams) estimates geothermal heat flux to be 69 ± 1 mW m^{-2} (Engelhardt, 2004), which is broadly consistent with the estimates of Maule (2005), given the error margin of 20–25 mW m^{-2}.

Geothermal heat flux is also hypothesised to influence ice velocities in the Greenland Ice Sheet. The onset of the Northeast Greenland Ice Stream, where melt rates of up to 0.2 m a^{-1} have been estimated, is proposed to overlay a caldera structure with a predicted heat flux of 970 mW m^{-2} (Fahnestock et al., 2001) This is an order of magnitude higher than the mean heat flux of Greenland, which is estimated at 51.3 mW m^{-2} (Dahl-Jensen et al., 1998), and has therefore been postulated to influence the location of the ice stream.

Quaternary ice sheets offer good opportunities to investigate the links between ice streaming and geothermal heat flux because they allow direct measurement of heat flux, albeit post ice sheet occupation. However, the only explicit investigation of geothermal heat flux and ice streaming is that of Bourgeois et al. (2000) on the Late Weichselian Icelandic Ice Sheet. Using mega-scale geomorphic mapping to identify the "main ice routes", three of which have good evidence to suggest that they are palaeo-ice streams, the authors note that all except four of these are located in areas with geothermal heat fluxes in excess of 150 mW m^{-2}.

These studies emphasise the potential sensitivity of ice streams to geothermal heat flux, with relatively small changes capable of triggering large changes in basal conditions. Even for ice sheets outside tectonically active regions, geothermal heat flux variations may have an importance influence on basal melt rates, making this a potential control on ice streaming.

9. Meltwater routing

9.1. Theory

It has been found that the water pressure beneath Whillans Ice Stream, West Antarctica, is almost at ice floatation pressure (Engelhardt and Kamb, 1997; Kamb, 2001), suggesting that meltwater availability is fundamental to the fast flow of ice streams. The routing of meltwater may influence ice stream location in both hard and soft bed areas. In hard bed areas, the presence of meltwater decouples ice from the bed, permitting sliding and thereby promoting fast flow. In soft bed areas, meltwater promotes fast flow by saturating basal sediments, permitting their deformation and/or sliding across their surface. Both processes are dependent on subglacial water pressure which varies spatially and temporally depending on the distribution of water, the nature of the subglacial meltwater system, the underlying geology, the basal ice temperature and the ice overburden pressure (Clarke, 2005).

Despite its likely importance, knowledge of sub-ice stream hydrological systems remains incomplete, making it difficult to assess the influence of meltwater on ice stream location. Early work estimated large melt rates beneath West Antarctic ice streams (~20 mm a^{-1}), suggesting that sufficient meltwater was generated beneath the ice streams to lubricate their beds (Shabtaie and Bentley, 1987). With the discovery that the lateral margins, rather than the bed, support much of the driving stress, these estimates were lowered (Raymond, 2000). Evidence now suggests that the beds of ice streams are a mosaic of melting and freezing, with basal melting difficult to maintain and freezing often dominating (Joughin et al., 2004b). This means that in order to maintain their lubrication, meltwater must be supplied from upstream (with the exception of sticky spots where strain heating is high), necessitating the existence of an efficient means of routing meltwater downstream (Parizek et al., 2002; Joughin et al., 2004b).

Suggestions of the form of such a drainage system include a thin film of water beneath the ice (Weertman, 1972), a linked-cavity system (Kamb, 1987), a channelized system either incised into bedrock or subglacial sediments (Hooke, 1989; Walder and Fowler, 1994; Ng, 2000) or a saturated mass of deformable sediments (e.g. Alley et al., 1986; Tulaczyk et al., 2000a). Recent data from Rutford Ice Stream suggests that multiple hydrological systems may be present beneath a single ice stream. Murray et al. (2008) identify discrete areas of basal sliding and bed deformation beneath the ice stream, each with a different hydrological system. In areas of basal sliding, they suggested that water availability is spatially variable and where present, takes the form of relatively small bodies of water, such as cavities at the bed. In contrast, in areas of bed deformation water was focused in channels ~50 m wide, incised into the basal sediments.

Extensive networks of meltwater channels have been observed on palaeo-ice stream beds in areas of crystalline bedrock (Lowe and Anderson, 2003; Domack et al., 2006; Anderson and Fretwell, 2008) and in sedimentary substrate (Wellner et al., 2006). On the crystalline bedrock of the inner shelf of Pine Island Bay, West Antarctica, several types of channel are identified. The largest are deep, linear tunnel valleys, incised over 400 m into bedrock and with diameters of 15×2 km. Branched, tunnel valleys and anatomizing channels are also seen, which are smaller in size (Lowe and Anderson, 2003). The abundance and morphology of these features demonstrates the presence of large volumes of freely moving subglacial meltwater, with the possibility of periodic meltwater outburst floods. On the sedimentary substrate of the outer shelf there is clear evidence for ice streaming in the form of mega-scale glacial lineations, yet geomorphic evidence of meltwater is less common (Lowe and Anderson, 2002; Evans et al., 2006). Abundant gullies seaward of the shelf break demonstrate that meltwater was present in this zone (Dowdeswel et al., 2006) and one suggestion is that melt was incorporated into sub-ice stream deformation till, providing a mechanism for fast ice flow.

9.2. Evidence

The authors are not aware of any palaeo-ice streams whose locations' are suggested to have been controlled by subglacial meltwater routing, but this issue has been the focus of several recent studies in Antarctica. Indeed, the critical importance of subglacial meltwater to ice streaming has been linked to the stagnation of Kamb Ice Stream, West Antarctica, which has been attributed to re-routing of its subglacial meltwater supply to the neighbouring Whillans Ice Stream (Anandakrishnan and Alley, 1997). The same explanation is proposed for Carlson Inlet, also in West Antarctica, with its stagnation attributed to the diversion of meltwater towards the neighbouring Rutford Ice Stream (Vaughan et al., 2008).

Hulbe and Fahnestock (2004) use a numerical ice shelf model to investigate past changes in the flow and grounding line position of Whillans Ice Stream, West Antarctica and conclude that these reflect variations in meltwater availability. They contend that the temperature gradient in basal ice determines meltwater availability. Upstream on Whillans Ice Stream the ice is relatively thick, and the temperature gradient in the basal ice is low, thereby favouring meltwater production. Downstream, as the ice thins, the basal temperature gradient steepens, and this favours basal freezing. These changes are manifest as the observed deceleration of Whillans Ice Stream's ice plain. They propose that "where basal meltwater is abundant and distributed, ice streams will flow fast, and where basal meltwater is scarce, they will not" (Hulbe and Fahnestock, 2004, p. 481).

Recent observations from Antarctica have also highlighted a potential link between subglacial lakes and ice streaming. Fig. 8 shows four subglacial lakes which have been identified upstream of the onset of Recovery Ice Stream (Bell et al., 2007). Similar areas of significant subglacial meltwater storage have been mapped upstream of Bindschadler, Kamb and Whillans Ice Streams (Gray et al., 2005; Fricker et al., 2007; Peters et al., 2007). In these cases, vertical movement of the ice surface over sites of subglacial water storage

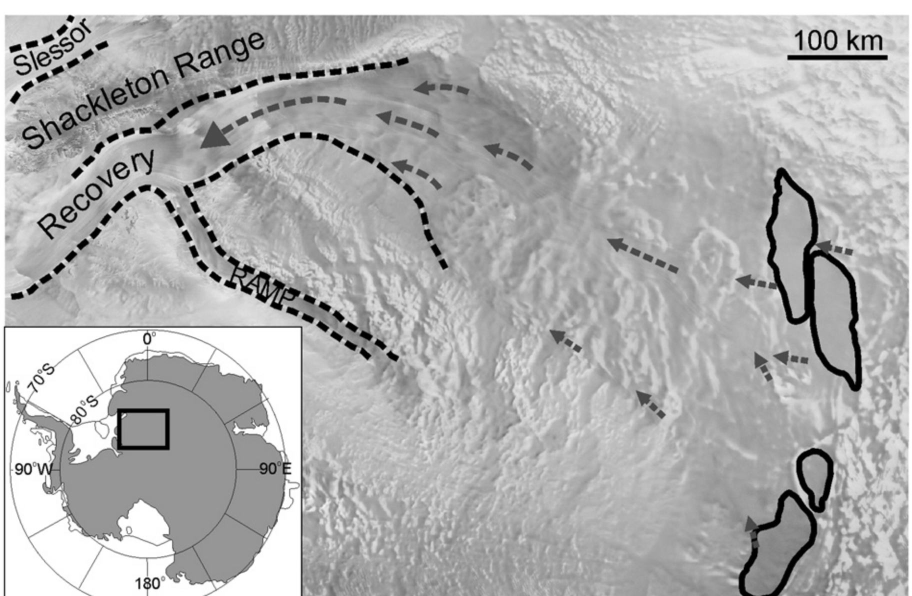

Fig. 8. RADARSAT image of the onset and catchment of Recovery Ice Stream, West Antarctica (modified from Bell et al., 2007). Ice stream margins are indicated by dotted black lines. Grey arrows indicate ice flow direction and black outlines mark the areas with flat ice surfaces, interpreted as Recovery subglacial lakes. Inset map shows the location of the RADARSAT image in Antarctica.

Table 1
Hypothesised controls on the location of selected contemporary and palaeo-ice streams.

Ice stream(s)	Ice sheet	Proposed control mechanism(s)	Reference(s)
Jakobshavn Isbræ	Greenland Ice Sheet	Topographic focusing	Truffer and Echelmeyer (2003), Clarke and Echelmeyer (1996)
Northeast Greenland Ice Stream	Greenland Ice Sheet	Geothermal heat flux	Fahnestock et al. (2001)
Siple Coast Ice Streams	West Antarctic Ice Sheet	Subglacial geology	Bell et al. (1998), Studinger et al. (2001), Anandakrishnan et al. (1998), Peters et al. (2006)
		Geothermal heat flux	Blankenship et al. (1993)
		Meltwater routing	Anandakrishnan and Alley (1997), Hulbe and Fahnestock (2004), Peters et al. (2007)
		Macroscale bed roughness	Siegert et al. (2004)
Evans Ice Stream	West Antarctic Ice Sheet	Subglacial geology	Vaughan et al. (2003)
Institute and Möller Ice Streams	West Antarctic Ice Sheet	Macroscale bed roughness	Bingham and Siegert (2007)
		Subglacial geology	Bingham and Siegert (2007)
Rutford Ice Stream	West Antarctic Ice Sheet	Topographic step	McIntyre (1985)
		Subglacial geology	Smith (1997), Doake et al. (2001)
Carlson Inlet	West Antarctic Ice Sheet	Meltwater routing	Vaughan et al. (2008)
Byrd Glacier	East Antarctic Ice Sheet	Topographic step	McIntyre (1985)
Slessor Glacier	East Antarctic Ice Sheet	Subglacial geology	Bamber et al. (2006)
Recovery Ice Stream	East Antarctic Ice Sheet	Meltwater routing	Bell et al. (2007)
Norwegian Channel Ice Stream	Fennoscandian Ice Sheet	Topographic focusing	Sejrup et al. (2003)
	Western margin of Fennoscandian Ice Sheet	Topographic focusing	Ottesen et al. (2005)
	Northern and western margin of Laurentide Ice Sheet	Topographic focusing	De Angelis and Kleman (2007), Stokes et al. (2009), Shaw et al. (2006)
Hudson Strait	Laurentide Ice Sheet	Topographic focusing	Andrews and Maclean (2003)
		Subglacial geology	MacAyeal (1993)
Dubawnt Lake	Laurentide Ice Sheet	Calving margin	Stokes and Clark (2004)
e.g. Des Moines Lobe	Southern margin of Laurentide Ice Sheet	Subglacial geology	Clark (1994)
Skjalfandi, Hvita and Axarfjordur	Icelandic Ice Sheet	Geothermal heat flux	Bourgeois et al. (2000)

have been observed and are hypothesised to reflect the drainage of water from one location of storage to another (Gray et al., 2005; Fricker et al., 2007; Peters et al., 2007). Based on these observations it has been suggested that the location of the ice streams is influenced by the presence of subglacial lakes; which encourage fast ice flow through the supply of subglacial meltwater, and/or through the erosion of bedrock channels during lake drainage events (Bell et al., 2007; Fricker et al., 2007; Peters et al., 2007). A possible association between subglacial meltwater drainage events and ice streaming is significant and has important implications for our understanding of both subglacial hydrology and ice stream dynamics. Subglacial meltwater routing is likely to be crucial to ice stream operation and yet it is also one of the most poorly understood aspects of glaciology.

10. Discussion

10.1. A hierarchy of controls on ice stream location?

Table 1 summarises the modern and palaeo- ice streams discussed in this paper, and the factors hypothesised to control their location. It is clear that there is no single, universal control on ice stream location and it is interesting to note that the best-studied ice streams, those of the Siple Coast, West Antarctica, have the highest number of suggested controls. Based on Table 1, the most commonly cited controls on ice stream location would appear to be topographic focusing, subglacial geology and subglacial meltwater routing. This is also the case for the Laurentide Ice Sheet, where preliminary investigations suggest that these same three controls, plus calving margins, were most frequently associated with the location of palaeo-ice streams (Winsborrow, 2007). Indeed, we propose that a hierarchy of controls exists (Fig. 9), which captures the likely influence of each of the hypothesised controls and determines where, within an ice sheet, ice streams might develop. In such a hierarchy, those controls which most commonly (strongly) influence ice stream location are closer to the top, and where present beneath an ice sheet are likely to be associated with ice streaming. In the absence of these controls, those lower down the hierarchy, which have a weaker influence, may become more important.

Based on the notion of a hierarchy of controls on ice stream location, we suggest that the presence of some ice streams is controlled predominantly by a single factor, whilst others require the operation of multiple factors. In the case of a single control, this is one which is alone sufficient to promote the initiation of fast flow, and determine the exact location of the ice stream. Such controls will tend to lie at the top of the hierarchy, for example topographic focusing. A more unusual example of this is the Dubawnt Lake Ice Stream,

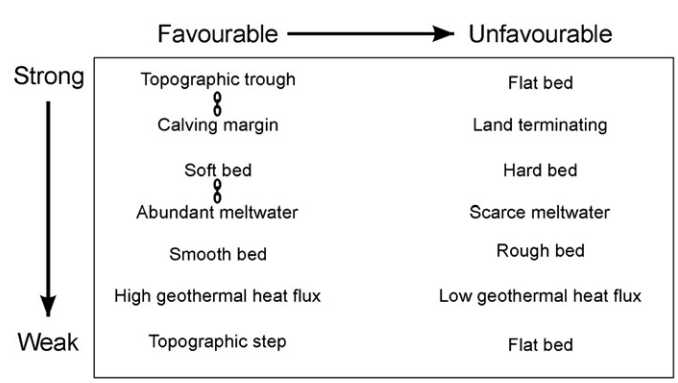

Fig. 9. Simple hierarchy of controls on the location of ice streams based on examples from the literature. Within such a hierarchy, topographic focusing and the presence of a calving margin are considered 'strong' controls on ice streaming. Secondary to this are favourable subglacial geology and meltwater routing. In the absence of either of these controls, other factors (such as a smooth bed, high geothermal heat flux or topographic step) may exert an influence.

Laurentide Ice Sheet, whose location was determined by a locally restricted calving margin (Stokes and Clark, 2004). More complex are those examples of ice streams whose locations are determined by the operation of several controls. The Siple Coast Ice Streams are likely to be an example of these, occurring in an area which is hypothesised to have favourable subglacial geology, meltwater routing, macro-scale bed roughness and geothermal heat flux. The exact position of these ice streams may reflect a delicate balance between several factors, with some factors more influential than others with respect to the proposed hierarchy. For example, although the now-stagnant Kamb Ice Stream lies over favourable subglacial geology and has a smooth bed, it seems that meltwater routing is the most important control. It could be hypothesised therefore, that although the Siple Coast ice streams might be associated with favourable subglacial geology and relatively smooth beds, they are most sensitive to meltwater supply.

10.2. Controls on the spatial and temporal variability of ice streams

In identifying the main controls on the location of ice streams, we also gain insights into their spatial and temporal stability. For example, large scale subglacial topography is relatively stable over a glacial cycle and so topographically constrained ice streams (e.g. topographic focusing) are likely to remain stable and fixed in their location. Any changes in their flow are likely a consequence of changes in additional, less stable controls. Such a scenario is seen on Jakobshavn Isbræ, which is topographically constrained but variations in calving rate have induced large variations in flow velocity (e.g. Truffer and Echelmeyer, 2003; Joughin et al., 2004a). A further example is the topographically constrained Bjørnøyrenna Ice Stream in the Barents Sea Ice Sheet, which underwent cycles of quiescence and fast flow, thought to relate to variations in subglacial meltwater and the strength of subglacial sediments (Andreassen and Winsborrow, 2009). We note, however, that over successive glaciations, the location of topographically constrained ice streams may switch position when accommodation space on continental margins is filled (e.g. Dowdeswell et al., 2006).

It is also important to note the time-scale over which each of the hypothesised controls may change in itself and thereby exert an influence on ice stream behaviour. For example, it is conceivable that subglacial meltwater routing can change over very short time-scales (almost instantaneously in the form of major drainage events) and result in relatively rapid changes in ice stream behaviour. Similarly, the presence of a calving margin could develop or disappear very quickly, perhaps as a result of ice shelf removal or proglacial lake drainage. Other controls vary over longer time-scales. Subglacial sediment thickness, bed roughness and topographic steps might be modified, as a result of subglacial erosion, over 100–1000s of years, resulting in more gradual change in ice stream behaviour. Likewise, major topographic troughs are likely to be stable (and indeed deepen) from one glaciation to the next, exerting an increasingly important control on ice stream location but no appreciable control on ice stream behaviour. Table 2 summarises the time-scales over which each of the hypothesised controls is likely to influence ice stream behaviour.

In view of the above time-scales, it could be argued that ice streams which are primarily governed by subglacial meltwater supply and/or calving margins might exhibit more variable behaviour because both of these factors vary spatially and temporally (an extreme example being the proposed subglacial lake drainage events beneath Antarctica, see section 9.2). Examples of this are the Siple Coast Ice Streams which show large fluctuations in their flow regimes (e.g. Conway et al., 2002; Joughin et al., 2005; Catania et al., 2006) and the southern margin of the Laurentide Ice Sheet which is proposed to have underground surge-type behaviour in response to fluctuations in subglacial meltwater pressure (Clayton et al., 1985).

The dominant control(s) on ice stream location will also determine their sensitivity to sticky spots. Sticky spots are localised area of high basal drag and are thought to be caused by subglacial bumps, patches of till-free areas, patches of stronger till, and patches of basal freezing (Alley, 1993; Stokes et al., 2007). Ice streams primarily controlled by meltwater routing might be particularly susceptible to sticky spots caused by changes in the supply and/or configuration of meltwater, e.g. if some areas of till are starved of meltwater, they could stiffen and increase the basal shear stress. Those ice streams influenced by geothermal heat flux might be particularly sensitive to basal freeze-on sticky spots if, over medium time-scales, the heat flux is diminished. Similarly, those ice streams governed by subglacial geology and the availability of soft, find-grained till, might be particularly susceptible to till-free sticky spots, should till continuity (i.e. the balance between till generation and transport) become inhibited.

The type of control will also influence the susceptibility of an ice stream to inland and lateral migration. Ice streams with strong topographically constrained lateral margins have little potential for lateral migration, and changes in ice flux must therefore be accommodated through changes in ice stream length, or changes in ice removal at the terminus. Fig. 4 shows the macro-scale bed roughness estimated beneath three of the Siple Coast Ice Streams (Siegert et al., 2004). If this is the primary control on their location, then the rapid increase in total roughness beyond their margins would limit the extent of any lateral migration. If, however, the location of the Siple Coast Ice Streams is primarily determined by the subglacial geology, as proposed by Studinger et al. (2001), based on their proposed distribution of subglacial sediments (Fig. 6) lateral migration of these ice stream should be expected, but inland migration is unlikely.

10.3. Issues of causality

A weakness in our analysis of ice stream controls is a methodological reliance on *associations* between hypothesised controls and the reported incidence of fast flow. Even where the spatial co-incidences are valid, the association is not always revealing with regard to the direction of causality. We may ask, for example, whether Jakobshavn Isbræ is controlled by the topographic trough in which it sits, or whether an 'early' ice stream decided to locate here and over time eroded the trough. Reconstructions of the long-term behaviour of palaeo-ice streams can provide further insights in this regard. For example, the Norwegian Channel Ice Stream (Sejrup et al., 2003) cut into soft sediments and the profligate amount of sediment exported from it (Nygård et al., 2007) suggests that the channel itself may, initially at least, be a consequence of ice streaming. Likewise, geothermal anomalies were argued by Bourgeois et al. (2000) to exert a strong control on palaeo-ice stream location in Iceland. However, a corollary of these anomalies are the springs of hot water delivered to the ice sheet bed and which are preferentially routed into the valleys (i.e. low points) where the ice streams are located. Maybe the ice streams cut the valleys and thus preferentially captured the springs. Indeed, even the association between an ice stream location and a hypothesised control could be questioned because, in some cases, the main ice stream trunk may have developed in response to a 'control' that exists some distance up-ice in the catchment area.

Table 2
Time-scales over which hypothesised controls on ice stream location may change and influence ice stream behaviour.

Hypothesised control	Time-scale of change
Meltwater routing	Short (<1–100 a^{-1})
Calving margin	Short (<1–100 a^{-1})
Bed roughness	Medium (100–1000 a^{-1})
Geothermal heat flux	Medium (100–1000 a^{-1})
Subglacial geology/till thickness	Medium (100–1000 a^{-1})
Topographic step	Medium (100–1000 a^{-1})
Topographic focusing	Long (1000–100,000 a^{-1})

A further concern regarding such circularities is the consideration of bed roughness on streaming. That ice streams prefer smooth locations may well be significant, but it is also certainly true that they smooth the bed through the activity of streaming; as demonstrated by the formation of megascale glacial lineations (e.g. Stokes and Clark, 2002; King et al., 2009). In all of these cases, history is important but ascertaining which came first (the ice stream or the control) is, of course, often difficult to resolve. We also need to consider that the location of some ice streams might be determined by historical conditions that no longer exist. At the Last Glacial Maximum, the Antarctic and Greenland ice sheets were considerably larger than present and maybe some of the current ice stream corridors were controlled by the ice sheet configuration at this time. Thus, in some cases their positions may be inherited.

Despite these difficulties regarding which came first and the issue of inheritance, we regard our analysis as an exploratory step in deciphering the controls on ice stream location and initiation. We hope that this framework may stimulate further work on this type of 'template matching' or motivate numerical modelling experiments that test these hypotheses. Insightful modelling experiments could proceed thus; given a flat uniform bed and a naturally-arising self-organised network of ice streams, by how much do we need to change controlling parameters (e.g. basal topography, distribution of heat or sediment) to initiate or destroy ice streams or move or anchor them? Such an approach could reveal the extent to which the various controls matter, and importantly, inform us about how sensitive our current ice streams are to future more dramatic changes in their ice flux.

11. Conclusions

The spacing of ice streams within contemporary and palaeo-ice sheets is not uniform, indicating that factors other than just internal glaciological dynamics (i.e. self-organisation) control their location. We have collated seven potential controls on ice stream location postulated in the literature: topographic focusing, topographic steps, topographic roughness, calving margins, 'soft' subglacial geology, geothermal heat flux and subglacial meltwater routing. The theoretical basis for each control has been introduced, followed by examples of its influence on contemporary and palaeo-ice streams. Based on this analysis we conclude that there is no single control on ice streaming, but that topographic focusing, 'soft' subglacial geology, subglacial meltwater routing and calving margins are most commonly associated with fast ice flow. We suggest that a hierarchy of controls determines where ice streams will operate, with topographic focusing in the presence of a calving marine the primary control on ice streaming. In the absence of this, locations with favourable subglacial geology and abundant subglacial meltwater supply may be associated with ice streaming. In the absence of these, smooth beds, high geothermal heat fluxes and topographic may be sufficient to promote ice streaming. The factors which control ice stream location will influence their spatial and temporal dynamics, with ice streams controlled by meltwater routing or calving processes potentially susceptible to more rapid changes than those controlled by factors that vary over longer time-scales e.g. geothermal heat flux, subglacial roughness, geology and topography.

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