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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