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Distribution and characteristics of overdeepenings beneath the Greenland and Antarctic ice sheets: Implications for overdeepening origin and evolution

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ABSTRACT

Glacier bed overdeepenings are ubiquitous in glacier systems and likely exert significant influence on ice dynamics, subglacial hydrology, and ice stability. Understanding of overdeepening formation and evolution has been hampered by an absence of quantitative empirical studies of their distribution and morphology, with process insights having been drawn largely from theoretical or numerical studies. To address this shortcoming, we first map the distribution of potential overdeepenings beneath the Antarctic and Greenland ice sheets using a GIS-based algorithm that identifies closed-contours in the bed topography and then describe and analyse the characteristics and metrics of a subset of overdeepenings that pass further quality control criteria. Overdeepenings are found to be widespread, but are particularly associated with areas of topographically laterally constrained ice flow, notably near the ice sheet margins where outlet systems follow deeply incised troughs. Overdeepenings also occur in regions of topographically unconstrained ice flow (for example, beneath the Siple Coast ice streams and on the Greenland continental shelf). Metrics indicate that overdeepening growth is generally allometric and that topographic confinement of ice flow in general enhances overdeepening depth. However, overdeepening depth is skewed towards shallow values – typically 200–300 m – indicating that the rate of deepening slows with overdeepening age. This is reflected in a decline in adverse slope steepness with increasing overdeepening planform size. Finally, overdeepening long-profiles are found to support headward quarrying as the primary factor in overdeepening development. These observations support proposed negative feedbacks related to hydrology and sediment transport that stabilise overdeepening growth through sedimentation on the adverse slope but permit continued overdeepening planform enlargement by processes of headward erosion.

1. Introduction

Closed topographic depressions in the beds of present and former ice masses – also known as 'overdeepenings' – are an implicit feature of glaciated landscapes (e.g. Linton, 1963; Cook and Swift, 2012). Arguably, process understanding of overdeepening formation and significance has been disadvantaged by an absence of quantitative empirical studies of their distribution and morphology (Cook and Swift, 2012; Patton et al., 2015), which contrasts sharply with the availability of empirical data for other subglacial phenomena, such as drumlins (Clark et al., 2009). Awareness of this landform type is growing, most notably because the reverse-bed gradients created by overdeepenings are known to reduce subglacial drainage system transmissivity (e.g. Creyts and Clarke, 2010), thus affecting ice-bed coupling and basal sliding, and known to dispose marine-terminating outlet glacier systems to rapid, episodic retreat (e.g. Weertman, 1974; Thomas, 1979; Jamieson et al., 2012; Nick et al., 2009; Schoof, 2007). In addition, the amplitude and wavelength of subglacial topography is fundamental to the rate of glacier sliding because basal drag is sensitive

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to obstacle scale and, in particular, slope (Schoof, 2005). A dearth of empirical data not only hampers our ability to build generalised views of overdeepening origin and evolution, but also our ability to develop and test numerical models that couple glacial and landscape processes.

Overdeepenings are found in a wide variety of contexts, including glacier troughs and trough confluences (Fig. 1A&B), and beneath glacier and ice stream termini (Fig. 1C; Haeberli et al., 2016, Table 1 in Cook and Swift, 2012). The origin of these features has been debated widely. The focussing of ice flow, which can occur in troughs and especially at trough confluences, has been shown theoretically to increase erosion potential (e.g. Anderson et al., 2006; Kessler et al., 2008; Lloyd, 2015). However, the occurrence of overdeepenings in other contexts has focussed attention on the possibility of independent positive feedbacks that promote focussed, deep erosion of the bed (illustrated in Fig. 2) (Cook and Swift, 2012). Hooke (1991) proposed that overdeepenings might initiate because bed irregularities cause crevassing at the ice surface that should enhance the quarrying rate at these locations via the delivery of large volumes of surface melt to the bed. Hooke (1991) further proposed that amplification of the irregularity would further enhance the quarrying rate. Others (e.g. Alley et al., 1997; Herman et al., 2011) have emphasised enhanced erosion in the ablation zone driven by abundant surface melt motivating fast glacier sliding and fluvioglacial sediment flushing. Chains of overdeepenings have been suggested to arise from lithological variabilities that produce suitable initial bed irregularities (e.g. Glasser et al., 1998) but also wave-like instabilities in ice flow that should result in overdeepenings with regular spacing and amplitude (Mazo, 1989).

Overdeepenings are able to form in glacier and ice sheet beds because positive ice surface gradients permit ice and subglacial water to ascend adverse subglacial slopes. Evacuation of sediment by ice and water flow thus permits continued ice-bed erosion and therefore continued enlargement of the deepening basin. However, Shreve (1972) and Röthlisberger (1972) observed that adverse slopes impose limitations on the flow of subglacial water such that a hydraulically efficient channel that ascends an adverse slope that exceeds a threshold relation of around -1.6 times the ice surface slope will begin to close (the exact value is dependent on the parameters used; see Werder (2016)). Hooke (1991) proposed that this feedback should stabilise overdeepening development by restricting the transport of sediment by water and thus depositing a layer of till. Subsequent theoretical work (Alley et al., 1998, 2003; Creyts and Clarke, 2010) has supported the proposed importance of this feedback, and observations of overdeepening basal water pressures at near-overburden pressure (see Cook and Swift, 2012) support a switch in drainage transmissivity. Unfortunately, examination of the adverse bed slope to ice surface slope relation for Quaternary overdeepenings is unlikely to provide significant insight into their formation because (a) the ice geometry relevant to the period of formation cannot be known and (b) high water pressures and sediment deposition in overdeepenings reduces drag exerted by the bed (Cook and Swift, 2012), leading to a flattening of the ice surface above (cf. Haeberli et al., 2016). Further, theoretical work by Werder (2016) shows that the aforementioned threshold relation only represents the lower limit of the threshold at which channel closure occurs.

To stimulate new observational studies and the development of numerical ice-erosion models (e.g. Egholm et al., 2012), we present an overview of overdeepening distribution and morphology beneath the present ice sheets, and examine how large quantitative datasets on overdeepening characteristics might inform our understanding of overdeepening origin and evolution. To achieve this aim, we first use an automated GIS-based approach described by Patton et al. (2015) to map overdeepenings in published bed-topography datasets for Greenland and Antarctica, and then apply strict quality control criteria to the mapped dataset prior to the analysis of a range of overdeepening metrics. We do not map overdeepenings in formerly glaciated environments because post-glacial processes in these environments, such as sedimentation and lake formation, tend to obscure overdeepening depth and extent (e.g. Preusser et al., 2010). Analyses of mapped overdeepening distribution and morphology are used to explore (i) overdeepening

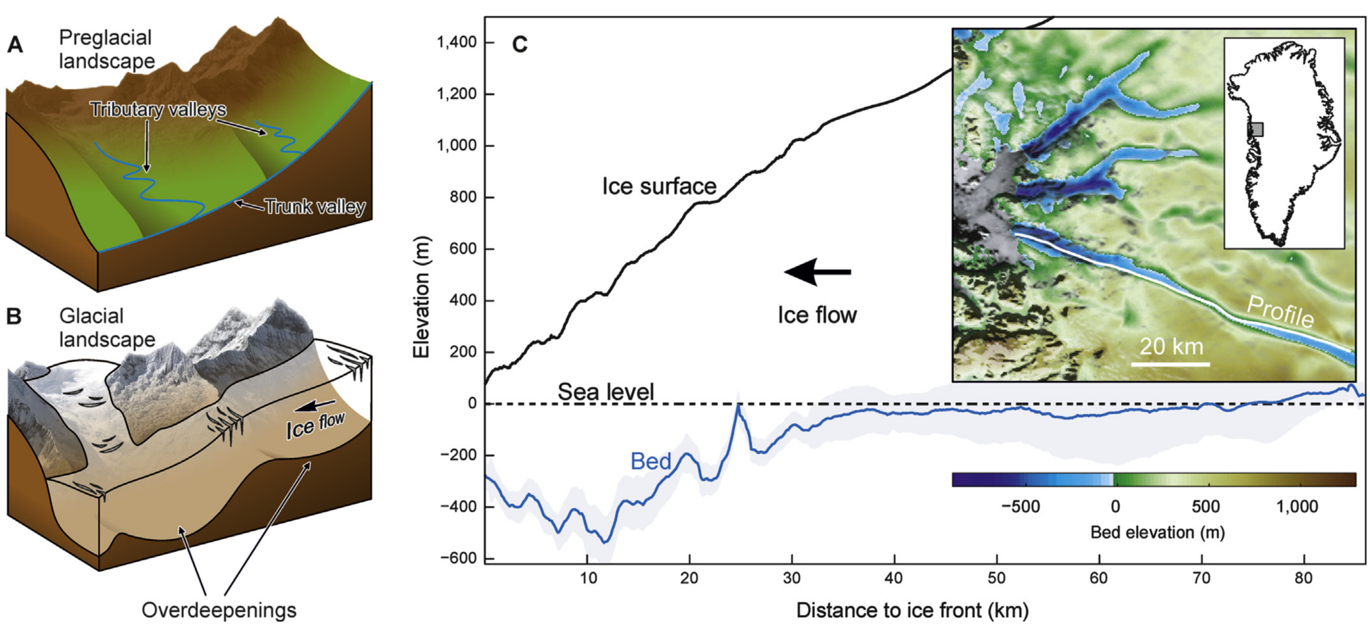

Fig. 1. Overdeepenings in valley glacier and in ice sheet outlet glacier contexts. A and B. Cartoon showing modification of a fluvial valley long-profile by glacial erosion, producing overdeepened basins. C. Overdeepenings in the bed of an outlet glacier in NW Greenland (redrawn from Morlighem et al., 2014). The location of the profile is shown in the inset. A large overdeepening extends some 30 km beneath the ice from the ice front and contains numerous 'nested' overdeepenings (the elevation axis is greatly exaggerated to show the bed topography).