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Antarctic palaeo-ice streams

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ABSTRACT

We review the geomorphological, sedimentological and chronological evidence for palaeo-ice streams on the continental shelf of Antarctica and use this information to investigate basal conditions and processes, and to identify factors controlling grounding-line retreat. A comprehensive circum-Antarctic inventory of known palaeo-ice streams, their basal characteristics and minimum ages for their retreat following the Last Glacial Maximum (LGM) is also provided. Antarctic palaeo-ice streams are identified by a set of diagnostic landforms that, nonetheless, display considerable spatial variability due to the influence of substrate, flow velocity and subglacial processes. During the LGM, palaeo-ice streams extended, via bathymetric troughs, to the shelf edge of the Antarctic Peninsula and West Antarctica, and typically, to the mid-outer shelf of East Antarctica. The retreat history of the Antarctic Ice Sheet since the LGM is characterised by considerable asynchroneity, with individual ice streams exhibiting different retreat histories. This variability allows Antarctic palaeo-ice streams to be classified into discrete retreat styles and the controls on grounding-line retreat to be investigated. Such analysis highlights the important impact of internal factors on ice stream dynamics, such as bed characteristics and slope, and drainage basin size. Whilst grounding-line retreat may be triggered, and to some extent paced, by external (atmospheric and oceanic) forcing, the individual characteristics of each ice stream will modulate the precise timing and rate of retreat through time.

1. Introduction

Ice streams are corridors of fast-flowing ice within an ice-sheet and are typically hundreds of kilometres long and tens of kilometres wide (Bennett, 2003). Their high velocities enable them to drain a disproportionate volume of ice and they exert an important influence on the geometry, mass balance and stability of ice sheets (e.g. Bamber et al., 2000; Stokes and Clark, 2001). Recent observations of ice streams in Antarctica and Greenland have highlighted their considerable spatial and temporal variability at short (sub-decadal) timescales and include acceleration and thinning, deceleration, lateral migration and stagnation (Stephenson and Bindschadler, 1988; Retzlaff and Bentley, 1993; Anandakrishnan and Alley, 1997; Conway et al., 2002; Joughin et al., 2003; Shepherd et al., 2004; Truffer and Fahnestock, 2007; Rignot, 2008; Wingham et al., 2009). The mechanisms controlling the fast and variable flow of ice streams and the advance and retreat of their grounding lines are, however, complex (Vaughan and Arthern, 2007) and a number of potential forcings and factors have been proposed. These include: (i) oceanic temperature (Payne et al., 2004; Shepherd et al., 2004; Holland et al., 2008; Jenkins et al., 2010); (ii) sea-level changes (e.g. Hollin, 1962); (iii) air temperatures (Sohn et al., 1998; Zwally et al., 2002; Parizek and Alley, 2004; Howat et al., 2007; Joughin et al., 2008); (iv) ocean tides (Gudmundsson, 2007; Griffiths and Peltier, 2008, 2009); (v) subglacial bathymetry (Schoof, 2007); (vi) the formation of grounding zone wedges (Alley et al., 2007); (vii) the availability of topographic pinning points (Echelmeyer et al., 1991); (viii) the routing of water at the base of the ice sheet (Anandakrishnan and Alley, 1997; Fricker et al., 2007; Stearns et al., 2008; Fricker and Scambos, 2009); (ix) the ice stream's thermodynamics (Christoffersen and Tulaczyk, 2003a; b); and (x) the size of the drainage basin (Ó Cofaigh et al., 2008). Resolving the influence of each of these controls on any given ice stream represents a major scientific challenge and it is for this reason that there are inherent uncertainties in predictions of future ice sheet mass balance (IPCC, 2007; Vaughan and Arthern, 2007).

An important context for assessing recent and future changes in ice streams and the controls on their behaviour is provided by reconstructions of past ice stream activity. It has been recognised that ice streams leave behind a diagnostic geomorphic signature in the geologic record (cf. Dyke and Morris, 1988; Stokes and Clark, 1999) and this has resulted in a large number of palaeo-ice streams being identified, mostly dating from the last glacial cycle and from both marine (e.g. Shipp et al., 1999; Canals et al., 2000; Evans et al., 2005, 2006; Ó Cofaigh et al., 2002, 2005a; Ottesen et al., 2005; Mosola and Anderson,

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Table 1
Proposed palaeo-ice streams of the Antarctic Ice Sheet during the last glacial period and the main lines of evidence used in their identification (numbers in square brackets refer to their location in Fig. 1, whilst those palaeo-ice streams with a question mark are less certain).

References	Ice stream	Drainage basin	Extent at LGM	Principle evidence for ice stream activity
Canals et al. (2000, 2003), Willmott et al. (2003) Evans et al. (2004), Heroy and Anderson (2005).	[1] Gerlache–Boyd	Western Bransfield Basin	Shelf-break	A convex-up elongate sediment body comprising parallel to sub parallel ridges and grooves (bundles) up to 100 km long; a convergent ice-flow pattern exhibiting a progressive increase in elongation into the main trough; and an outer-shelf sediment lobe seaward of the main trough.
Banfield and Anderson (1995), Canals et al. (2002), Heroy and Anderson (2005).	[2] Lafond	Central Bransfield Basin	Shelf-break	Deeply incised U-shaped trough with a drumlinised bed on the inner shelf and elongate grooves and ridges on the outer shelf; and a well developed shelf-edge lobe and slope debris apron.
Banfield and Anderson (1995), Canals et al. (2002), Heroy and Anderson (2005).	[3] Laclavere	Central Bransfield Basin	Shelf-break	Deeply incised U-shaped trough with a drumlinised bed on the inner shelf and elongate grooves and ridges on the outer shelf; and a well developed shelf-edge lobe and slope debris apron.
Banfield and Anderson (1995), Canals et al. (2002), Heroy and Anderson (2005).	[4] Mott Snowfield	Central Bransfield Basin	Shelf-break	Deeply incised U-shaped trough with a drumlinised bed on the inner shelf and elongate grooves and ridges on the outer shelf; and a well developed shelf-edge lobe and slope debris apron.
Bentley and Anderson (1998), Heroy et al. (2008)	[5] Orleans Trough	Central Bransfield Basin	?	A large cross-shelf trough. Streamlined bedforms including drumlins and scalloped features.
Canals et al. (2003), Amblas et al. (2006).	[6] Biscoe Trough	Antarctic Peninsula	Shelf-break	Biscoe Trough exhibits a convergent flow pattern at the head of the ice stream, with well-developed MSGL observed throughout. These bedforms show a progressive elongation towards the shelf edge, with the less elongate landforms on the inner shelf formed in bedrock and interpreted as roche moutonées.
Heroy and Anderson (2005), Wellner et al. (2006).	[7] Biscoe South Trough (=Adelaide Trough)	Antarctic Peninsula	?	A distinctive cross-shelf bathymetric trough characterised by rock cored drumlins on the inner shelf and MSGL on the outer shelf.
Pudsey et al. (1994), Larter and Vanneste (1995), Vanneste and Larter (1995), Domack et al. (2006).	[8] Anvers–Hugo Island Trough	Antarctic Peninsula	Shelf-break	Comprised of three tributaries which converge on a central trough. The inner-shelf is characterised by streamlined bedrock, and meltwater channels which cut across the mid-shelf high. The outer trough is floored by sediment and dominated by MSGL, with grounding zone wedges also identified in this zone.
Heroy and Anderson (2005).	[9] Smith Trough	Antarctic Peninsula	?	A cross shelf bathymetric trough containing streamlined bedrock features such as grooves and drumlins, with elongations ratios of up to 20:1.
Kennedy and Anderson (1989), Anderson et al. (2001), Wellner et al. (2001), Oakes and Anderson (2002), Ó Cofaigh et al. (2002, 2005b, 2007, 2008), Dowdeswell et al. (2004a, b), Anderson and Oakes-Fretwell (2008), Noormets et al. (2009), Kilfeather et al. (2011).	[10] Marguerite Trough	Marguerite Bay	Shelf-break	Streamlined subglacial bedforms occur in a cross-shelf bathymetric trough; the bedforms show a progressive down-flow evolution from bedrock drumlins and ice-moulded bedrock on the inner shelf to MSGL on the outer shelf in soft sediment; and the MSGL are formed in subglacial deformation till which is not present on the adjacent banks.
Ó Cofaigh et al. (2005a), Graham et al. (2010).	[11] Latady Trough	Ronne Entrance	?	MSGL located in a cross-shelf bathymetric trough.
Ó Cofaigh et al. (2005a), Dowdeswell et al. (2008b), Noormets et al. (2009), Hillenbrand et al. (2009, 2010a), Graham et al. (2010b).	[12] Belgica Trough	Eltanin Bay and Ronne Entrance	Shelf-break	Elongate bedforms are located in a cross-shelf bathymetric trough; the head of the ice stream is characterised by a strongly convergent flow pattern; the trough exhibits a down-flow transition from drumlins to MSGL, with the MSGL formed in subglacial deformation till; and large sediment accumulations have been observed including a TMF in front of Belgica Trough and a series of GZWs on the mid and inner shelf.
Anderson et al. (2001), Wellner et al. (2001), Lowe and Anderson (2002, 2003), Dowdeswell et al. (2006), Evans et al. (2006a, 2006b), Ó Cofaigh et al. (2007), Noormets et al. (2009), Graham et al. (2010a).	[13] Pine Island Trough	Pine Island Trough	Shelf-break	MSGL with elongation ratios of >10:1 in the middle/outer shelf composed of soft till formed by subglacial deformation; the bedforms are concentrated in a cross-shelf bathymetric trough; and a bulge in the bathymetric contours in-front of the trough indicates progradation of the continental slope.
Anderson et al. (2001), Wellner et al. (2001), Larter et al. (2009), Graham et al. (2009), Hillenbrand et al. (2010b), Smith et al. (2011).	[14] Getz–Dotson	Bakutis Coast	Shelf-break	Bedforms converge into a central trough from three main tributaries; the bedforms which occupy the trough have elongation ratios up to 40:1 and comprise drumlins, crag-and-tails and MSGL; MSGL on the outer shelf are formed in soft till; and the inner and mid-shelf contain a series of GZWs.
Wellner et al. (2001, 2006), Anderson et al. (2002).	[15] Wrigley Gulf	Wrigley Gulf	Outer-shelf/shelf break	A cross-shelf bathymetric trough containing drumlins and grooves on the inner shelf and MSGL on the outer shelf.
Wellner et al. (2001, 2006).	[16] Sulzberger	Sulzberger Bay	?	A prominent trough aligned with the structural grain of the coast. The bedrock floored trough is characterised by roche moutonées and erosional grooves which are

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