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A meltwater origin for Antarctic shelf bedforms with special attention to megalineations

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ABSTRACT

The geomorphology of troughs crossing the Antarctic shelf is described and interpreted in terms of ice-stream hydrology. The scale of tunnel channels on the inner shelf and the absence of sediment at their mouths are taken to infer catastrophic drainage. Drumlins on the inner and outer shelves with pronounced crescentic and hairpin scours are also interpreted as products of catastrophic flow. Gullies and channels on the continental slope and turbidites on the rise and abyssal plain point to abundant meltwater discharge across the shelf. Attempts to explain this morphology and sedimentology in terms of release or discharge of meltwater by pressure melting, strain heating, Darcian flow, or advection in deforming till are shown to be unrealistic. We suggest that meltwater flow across the middle and outer shelves might have been in broad, turbulent floods, which raises the possibility that megascale glacial lineations (MSGL) on the shelf might originate by erosion in turbulent flow. This possibility is explored by use of analogs for MSGL from flood and eolian landscapes and marine environments. An extended discussion reflects on objections that stand in the way of the flood hypothesis.

1. Introduction

Deep troughs cross the Antarctic continental shelf where distributary ice streams from the Antarctic Ice Sheets reached the ocean (e.g., Wellner et al., 2006). The shelf is subdivided along these troughs into inner, middle, and outer zones on the basis of geology and geomorphology. Outcrops or subcrops of igneous and sedimentary rock with high relief characterize the inner zone. Offshore-dipping sedimentary strata underlie thick surficial deposits on the outer shelf. The middle shelf marks the transition between the two. The geomorphology of the shelf, which is to a large extent controlled by the geological context, is considered here.

Numerous authors have written recently on bedforms in formerly glaciated Antarctic shelf-crossing troughs (e.g., Shipp et al., 1999; Canals et al., 2000; Wellner et al., 2001; Lowe and Anderson, 2002; Ó Cofaigh et al., 2002; Anderson, 2003; Gilbert et al., 2003; Dowdeswell et al., 2004; Ó Cofaigh et al., 2005; Heroy and Anderson, 2005; Wellner et al., 2006; Domack et al., 2006). A remarkably consistent sequence of trough bedforms extends from the inner shelf to the continental slope (Fig. 1). Megascale glacial lineations (MSGL; Clark, 1993; Fig. 2) are extensive on the shelf and understanding them is basic to an understanding of processes beneath paleo-ice streams.

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Although MSGL are generally interpreted as products of subglacial deformation of soft sediments, we show that similar megalineations form in broad, turbulent flows in water and air. These other lineations are worth considering as analogs for MSGL. If form and pattern are similar for the two sets of lineations and there is a case for broad, turbulent flows beneath former Antarctic shelf ice streams, a meltwater origin for MSGL is a promising alternative to formation by deforming deforming-bed processes. This possibility is explored here.

2. Shelf-crossing troughs, continental slope, and abyssal plain — geomorphology and sediment

2.1. Tunnel channels

Tunnel channels (e.g., Brennand and Shaw, 1994) are subglacial channels cut into the glacier substrate. Water in the channels commonly flowed uphill, giving them an undulating long profile. Tunnel channels may anastomose and they start and end suddenly. Other than boulders (Cutler et al., 2002), they rarely have deposits at their mouths. Kristensen et al. (2007) noted adverse gradients in channel end slopes and argued that this indicates high discharges with the generation of viscous heat. Otherwise, freezing of super-cooled meltwater would have sealed the channel. Tunnel channels contain coarse sediment (commonly boulders) and large-scale bedforms (Shaw and Gorrell, 1991), indicating high discharge. In some cases, large-scale fluting indicates that flow overtopped the rims of

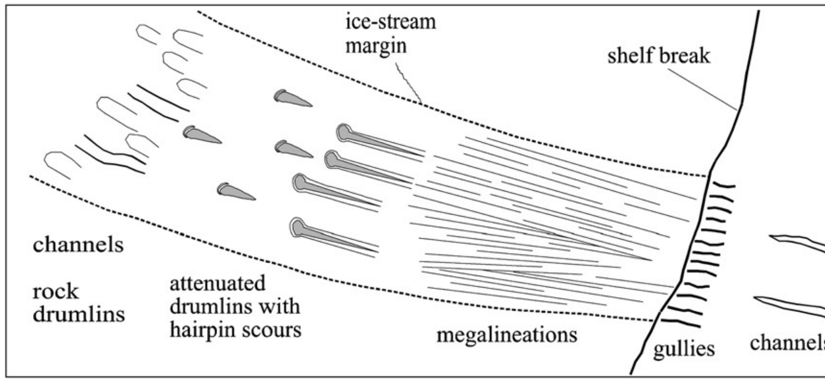

Fig. 1. Geomorphological model of a shelf-crossing trough formerly occupied by an ice stream.

tunnel channels (Shaw, 1988; Brennand and Sharpe, 1993; Shaw et al., 2000).

Antarctic tunnel channels with undulating long profiles are eroded into bedrock on the inner and middle shelves (Figs. 1 and 2B; Ó Cofaigh et al., 2002; Lowe and Anderson, 2003; Heroy and Anderson, 2005; Domack et al., 2006; Wellner et al., 2006). Antarctic shelf channels are on the scale of the largest tunnel channels of the Pleistocene low-latitude, continental ice sheets. For example, Lowe and Anderson (2002) described channels in Pine Island Bay up to 2.5 km wide and 400 m deep, and Ó Cofaigh et al. (2002) noted a 235-m deep channel in Marguerite Bay. Tunnel channels formed beneath low low-latitude ice sheets are commonly discontinuous; they begin and end abruptly with no fan deposits at their mouths (Rains et al., 2002; Sjogren et al., 2002; Golledge and Stoker, 2006; Kristensen et al., 2007). Antarctic tunnel channels show the same characteristics (Figs. 1 and 2B; Ó Cofaigh et al., 2002; Lowe and Anderson, 2003; Domack et al., 2006; Wellner et al., 2006). They commonly follow faults and joints (Domack et al., 2006).

2.2. Drumlins

Drumlins on the inner shelf are frequently eroded in bedrock and many have crescentic scours at their proximal ends (Fig. 4). Drumlins with scours occur in broad fields (Fig. 4; Gilbert et al., 2003; Heroy and Anderson, 2005; Wellner et al., 2006). Crescentic scours scale with drumlins, that is, scour width correlates with drumlin width (Fig. 4). Relative to bedforms on the middle and outer shelves, drumlins on the inner shelf have low length/width ratios. For example, Fig. 2A shows short, poorly developed drumlins in an area of closely spaced bedrock outcrops. The same relationship is seen in Fig. 3C where water-eroded bedforms created by broad flow in a flume are shorter where obstacles to flow are clustered and longer where obstacles are sparse. Antarctic shelf drumlins are usually confined to the inner shelf and the proximal parts of the middle shelf. Smith Trough is a notable exception with rock drumlins and grooves in bedrock extending across the whole shelf (Heroy and Anderson, 2005). Drumlins and exposed bedrock

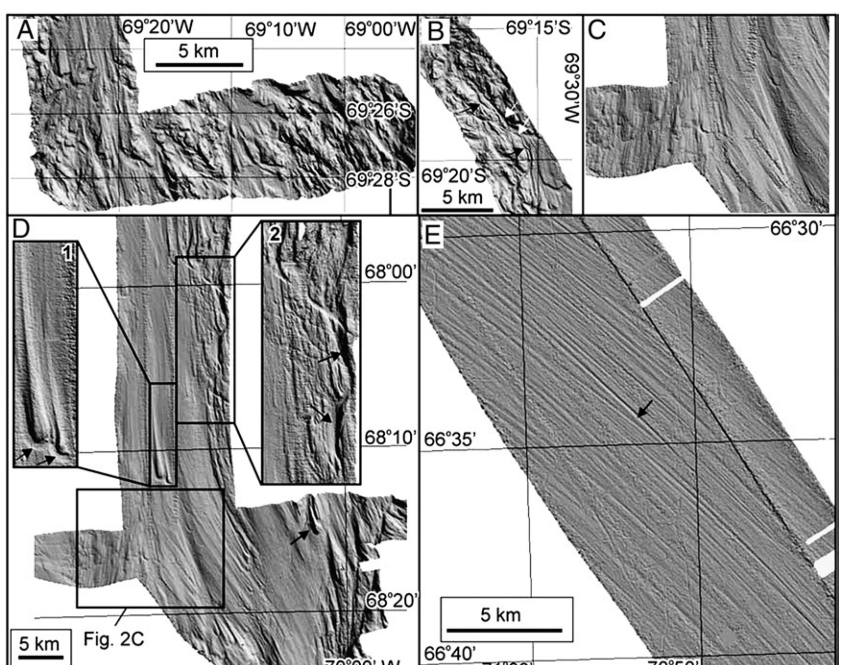

Fig. 2. EMI 120 shaded relief image of streamlined subglacial bedforms in Marguerite Trough, Antarctic Peninsula. (A) Short, irregular drumlins and incipient tunnel channels, inner Marguerite Bay. Grid cells 35 m × 35 m. (B) Meltwater channels in bedrock (arrowed), inner Marguerite Bay. Grid cells 35 m × 35 m. (C) Convergence of streamlined bedforms into the deepest point of the Marguerite Bay Trough. Grid cells 30 m × 30 m. (D) Drumlins and lineations formed in sediment and bedrock on the middle shelf. Grid cells 30 m × 30 m. Rat tail drumlin (arrowed) analogous with flume rat tails (C). Inset 1 shows drumlins with hairpin scours. Maximum height of drumlins is 120 m. Inset 2 shows a sinuous meltwater channel (arrowed). Maximum depth of the channel is 230 m. (E) megascale glacial lineations (MSGL) on the outer shelf. Maximum amplitude of the lineations is 15 m and transverse wavelengths range from 130 to 300 m. Cross-cutting of sets of lineations arrowed. Grid cells 25 m × 25 m. Figure from Ó Cofaigh et al. (2002), with permission from the American Geophysical Union.