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Ice-stream stability on a reverse bed slope

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Marine-based ice streams whose beds deepen inland are thought to be inherently unstable[1–3]. This instability is of particular concern because significant portions of the marine-based West Antarctic and Greenland ice sheets are losing mass and their retreat could contribute significantly to future sea-level rise[4–7]. However, the present understanding of ice-stream stability is limited by observational records that are too short to resolve multi-decadal to millennial-scale behaviour or to validate numerical models[8]. Here we present a dynamic numerical simulation of Antarctic ice-stream retreat since the Last Glacial Maximum (LGM), constrained by geophysical data, whose behaviour is consistent with the geomorphological record. We find that retreat of Marguerite Bay Ice Stream following the LGM was highly nonlinear and was interrupted by stabilizations on a reverse-sloping bed, where theory predicts rapid unstable retreat. We demonstrate that these transient stabilizations were caused by enhanced lateral drag as the ice stream narrowed. We conclude that, as well as bed topography, ice-stream width and long-term retreat history are crucial for understanding decadal- to centennial-scale ice-stream behaviour and marine ice-sheet vulnerability.

Ice streams are fast-flowing arteries of ice sheets that dominate ice discharge into the oceans, impacting directly on sea level. Many ice streams possess beds that are below sea level and typically deepen inland on a reverse slope[9]. Theory suggests that ice discharge increases rapidly with water depth[3], and in the absence of lateral-drag-induced buttressing from a floating ice shelf, grounding lines (marking the transition from grounded to floating ice) on reverse bed slopes may be unstable[1,2]. Bed topography is therefore cited as a strong control on ice-stream retreat rate[3,10] and modern satellite observations of rapid ice-stream thinning and recession seem consistent with this theory[4–6]. However, with just two decades of data, these records are too short to identify the longer-term centennial- to millennial-scale trends crucial for constraining future sea-level projections. Major uncertainties in predictions of ice-sheet vulnerability[11] relate to limitations in understanding processes controlling grounding-line motion and, importantly, to deficiencies in grounding-line treatment in ice-sheet models[12]. In recent years, significant advances in model development have been made[3,12–17], but tests have been applied only to simplified bed geometries or to steady-state conditions and lack validation against data over timescales longer than a few decades. We aim to understand the long-term controls and stability of marine ice streams and integrate a fully dynamic ice-stream model with the detailed geomorphological record of palaeo-ice-stream retreat imprinted on the sea floor of Marguerite Bay, western Antarctic Peninsula (Fig. 1).

High-resolution mapping from swath bathymetry and analysis of subglacial landforms and sediments[18–21] (Fig. 1 and Supplementary Information) identify the extent and evolution of the Marguerite Bay Ice Stream spanning several millennia following the LGM. After 14 kyr the grounding line retreated rapidly along an overdeepened trough with a reverse-sloping bed from its LGM position at the continental shelf edge[20]. However, within this rapid retreat, short-term grounding-line stability is recorded by a series of eight major wedge-shaped sedimentary landforms (grounding-zone wedges: GZWs)[18–20,22]. This evidence for temporary stability on reversed beds challenges the understanding of the controls on grounding-line behaviour. Indeed, palaeo-ice-stream retreat patterns are regionally inconsistent[20,23] indicating that although climate and ocean forcing are important, local controls such as basin geometry may modulate ice-stream retreat. We test this hypothesis using a time-dependent numerical ice-flow model.

The model[15,24] (Supplementary Information) considers variations in both along-flow bed geometry and ice-stream width, which are independently prescribed by marine geophysical observations. It includes resistive stresses from the bed and lateral margins, the transfer of stresses in upstream and downstream directions, a flotation criterion for calving and, crucially, a robust treatment of dynamic grounding-line behaviour that relies on a moving spatial grid. To assess ice-stream stability in the most unstable case, and because calving cannot be adequately constrained, the model has no ice shelf in the present treatment. A geophysically consistent steady-state LGM configuration extends to the continental shelf edge and provides the initial geometry (Supplementary Information and Fig. S1) for a series of retreat experiments forced by simple sea-level and climate trends. Water depth (−100 to 0 m a.s.l.) and ice temperature (−20 to -15 °C) are increased linearly over an 8 kyr period to represent average trends during deglaciation. The imposition of this linear external forcing allows us to identify and understand the potential internal mechanisms controlling ice-stream retreat (it is not our intention to reproduce the precise chronology).

In reference experiment A (Fig. 2 and Supplementary Movie S1), linear external forcing results in highly nonlinear stepped retreat of the grounding line across the outer and mid-shelf with several distinct phases of terminus slowdown with retreat rates of only a few metres per year. Once the grounding line retreats from the continental shelf break (triggered by the prescribed water-depth increase), the sensitivity of ice discharge to water depth modulates the retreat pattern, partly explaining the contrasting nonlinear response to linear forcing. For example, several retreat-rate slowdowns are consistent with the location of significant topographic highs, indicating the importance of bed morphology in defining pinning points (for example, at 500 km; Fig. 2). However, in the reverse-sloping portion of the bed and, significantly, in the absence of topographic highs, several slowdowns also occur. Moreover, the simulated stabilizations are broadly consistent with previously mapped GZW positions (Fig. 2). These short-term

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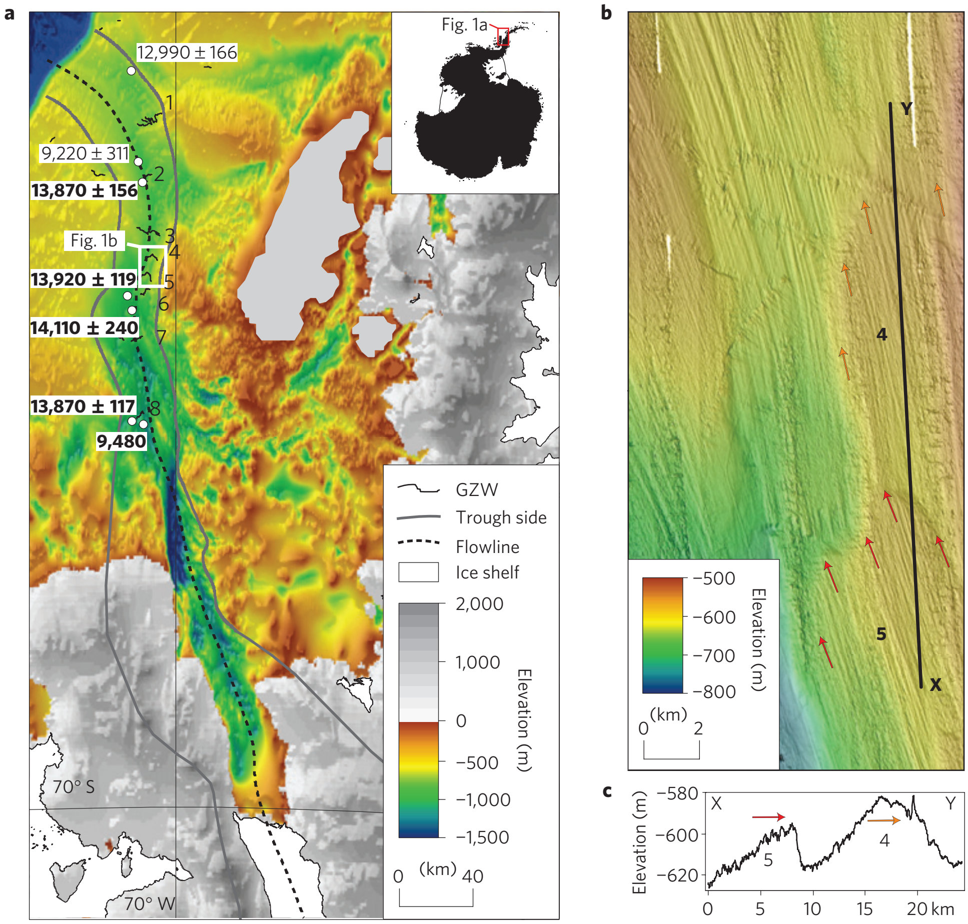

Figure 1 | Topographic map and ice-stream landform assemblage in Marguerite Bay. a, Model domain and mapped geophysical retreat constraints. GZWs 1–8 indicate palaeo-grounding line stabilizations. The white points show core locations[19,21,23] with corrected and calibrated accelerator mass spectrometry ^{14}C minimum retreat ages in years before present $\pm 1\sigma$ error (those in bold are the most reliable dates[23]). **b**, Morphology of GZWs 4 and 5 with arrows indicating their downstream limits and the direction of streaming ice flow determined from superimposed mega-scale glacial lineations. **c**, Profiles showing scale of GZWs 4 and 5. Arrows indicate ice flow direction during separate depositional phases (red versus orange).

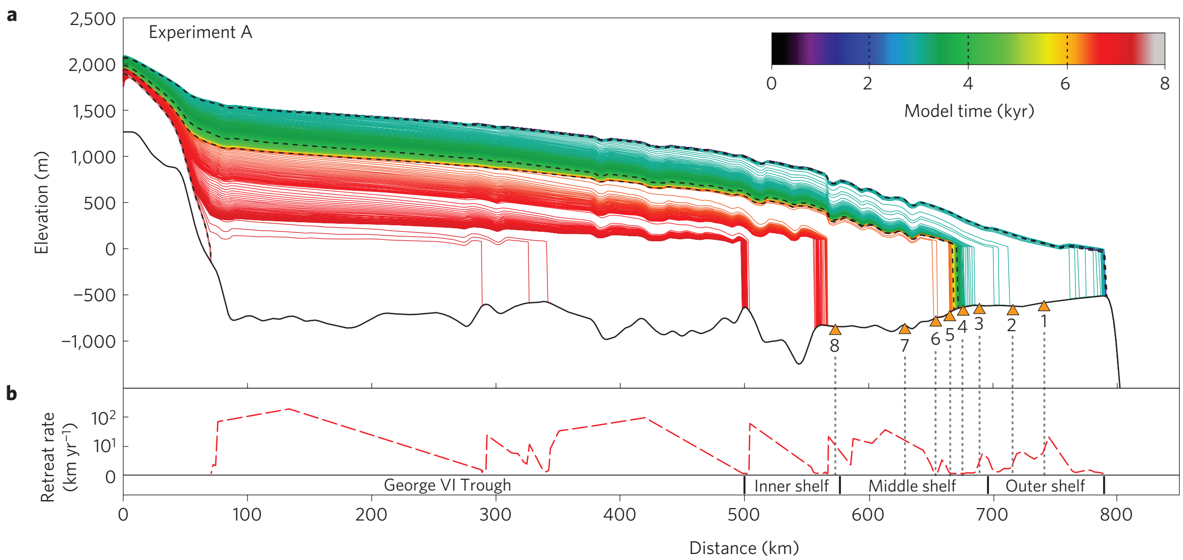

Figure 2 | Modelled ice-stream retreat characteristics for reference experiment A illustrating grounding-line stabilizations on a reverse bed slope. **a**, Coloured ice-surface profiles shown at 5 yr intervals over an 8 kyr period with dotted black lines highlighting ice surfaces every 2 kyr. The continuous black line shows the bed geometry. **b**, Modelled grounding-line retreat rate (dashed red line) on a logarithmic scale. The orange triangles and grey dashed lines show mapped GZWs 1–8 (Fig. 1). Where a large number of palaeo-ice-stream surfaces intersect the bed in **a**, slower retreat is observed in **b**.

changes in retreat rate occur adjacent to GZWs 1, 2, 3, 6, 7 and 8 and prolonged grounding-line stability is modelled between GZWs 4 and 5 where the reverse slope steepens into the overdeepened portion of Marguerite Trough. Further sensitivity experiments that accelerate sea-level rise and temperature increases confirm that the spatial pattern of retreat is not controlled by external forcing because the locations of grounding-line stability remain fixed with only the timing of the retreat phases changing.

Importantly, bed slope alone cannot explain the temporary stabilizations identified by the modelling and geomorphological data, indicating that other factors dominate over water depth. In particular, GZWs and retreat slowdowns coincide spatially with narrowing of the trough, implying that variations in ice-stream width (Fig. 1) are a potentially important control. It has been suggested that width variations may alter retreat rates in tidewater glaciers confined to fjords[25] but this has never been dynamically quantified on an ice-stream scale or over periods longer than a decade. To quantify the relative importance of the bed slope and width controls on ice-stream retreat behaviour we perform a series of experiments in which bed elevation and trough width are systematically modified.

Modelling experiment B is identical to A but imposes a horizontal bed over the outer 180 km of the continental shelf (Fig. 3). Again, simulated retreat behaviour is highly nonlinear, but the grounding line experiences only two significant stabilizations on the outer shelf (at GZW 2 and between GZWs 4 and 5). This nonlinear response is surprising given the flat bed and linear forcing, but we note that these slowdowns again coincide with narrowing of the ice-stream trough (Fig. 3).

Experiment C combines the flat bed of experiment B with a straightening of the ice-stream trough width over the outer 170 km of the continental shelf (Fig. 3). Nearly constant retreat rates of about 200 m yr^{-1} are obtained across the entire outer shelf, a pattern that is markedly different from the previous experiments and the geomorphological evidence.

Model experiment D further tests the importance of width by applying a linear reverse slope over the outer 180 km of the bed (Fig. 3). Although this induces rapid retreat over most of the outer shelf, a significant slowdown in retreat lasting about 50 years is nonetheless modelled between GZWs 4 and 6. This corresponds to the area of most significant trough narrowing (Fig. 3), demonstrating that unstable retreat associated with reverse beds can be temporarily overcome by constrictions in trough width.

These sensitivity experiments reveal that in addition to water depth, variations in ice-stream trough width play a fundamental role in controlling nonlinear retreat behaviour. We explain the width-controlled grounding-line stabilization effect using two mechanisms. First, lateral resistance from the sides of the ice stream increases as its width narrows[26] (Supplementary Figs S2 and S3), thereby reducing the ice flux required to maintain a stable grounding line. This is particularly effective when the bed provides limited resistance, for example in the proximity of the grounding line. Lateral shear stress is consistently 50% higher over the narrow zone of GZWs 3–5 than in adjacent areas (Supplementary Figs S4 and S5) and evolves only marginally as the grounding line retreats through this region. In contrast, basal shear stresses are significantly lower in this area and drop further as driving stresses are reduced and the ice stream thins and retreats. The enhanced zone of lateral shear stress is not present in constant-width experiment C (Supplementary Figs S2 and S3) and thus stabilizations do not occur. Second, the principle of mass conservation requires ice-sheet thickening and consequent surface steepening where ice streams narrow, which, for a given rate of surface thinning or sea-level change, leads to reduced retreat rates. The steeper surface enhances driving stress and thereby basal stress as suggested for tidewater systems[25] but, in our models, the reduction in basal

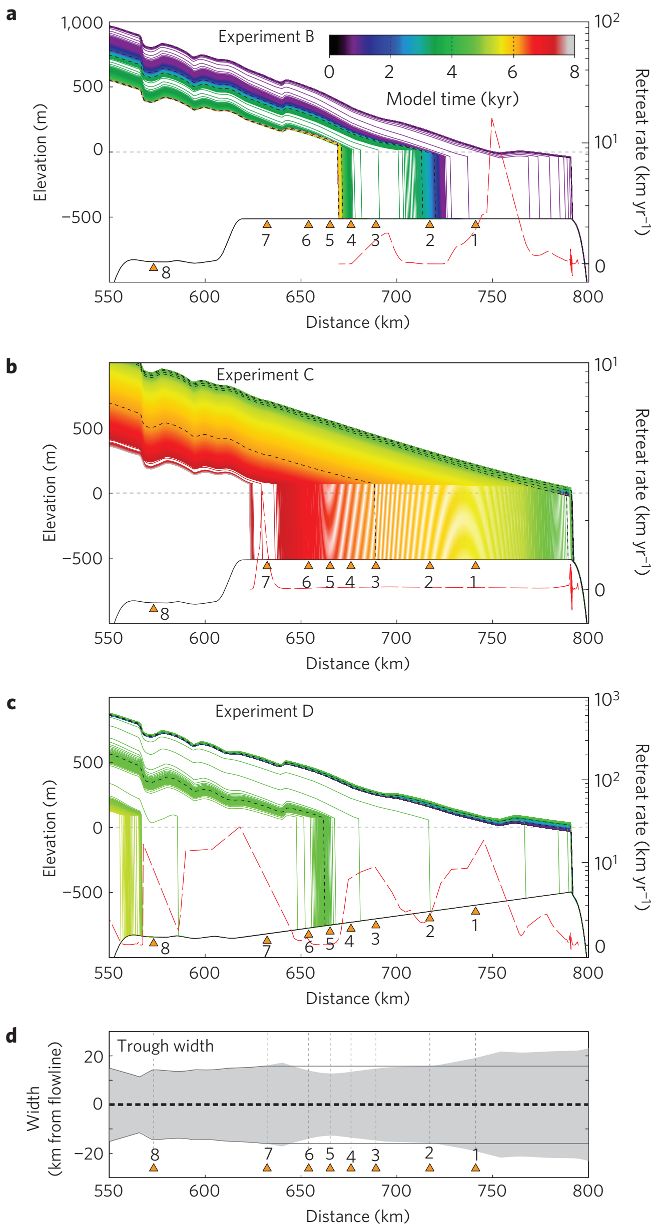

Figure 3 | Ice-stream retreat behaviour and imposed geometries for experiments B–D. a–c, Coloured ice-surface profiles at 2 yr intervals with dashed black lines every 2 kyr. The black lines plot imposed bed topographies; the dashed red lines show grounding-line retreat rates. The orange triangles represent GZWs 1–8 (Fig. 1). **d**, Mapped trough width (grey shading) applied in experiments A, B and D and imposed straightening of trough width (dark grey lines) in experiment C. Note that retreat onset timings vary because modification of trough width or bed depth alters ice-flux patterns. This does not affect the main finding of controls on retreat.

stress during retreat (Supplementary Fig. S2) is a response to evolving surface geometry rather than a first-order control for grounding-line retreat.

Although the above two factors explain the mechanism for transient grounding-line stabilization, the duration of stability is further dependent on the rate of inland-ice delivery to the grounding line. During stabilizations at width constrictions, thinning ceases near the grounding line but continues to propagate inland (Fig. 2) through direct longitudinal stress coupling and a time-transient feedback between accelerated ice flux and thinning[27]

(Supplementary Figs S4 and S5). This upstream surface drawdown delivers extra ice to the grounding line that acts to slow the retreat and maintain grounding-line stability. When the inland ice storage is depleted, the next phase of rapid retreat is initiated. The timescale of stabilization is therefore sensitive to both the volume of upstream ice within the catchment area and the degree of dynamic coupling between the grounding line and the upstream basin. As upstream propagation of thinning increases with ice speed[27,28], the weak sedimentary bed beneath Marguerite Bay Ice Stream[19] explains the tight coupling between grounding-line stability and the upstream basin. In the context of assessing ice-sheet mass balance, it is worth noting that even during phases of limited retreat, when short-term measurements would suggest ice-stream stability, mass loss through the grounding line is in reality enhanced significantly by several tens of per cent over decades to centuries through drawdown of ice from upstream (experiment A; Supplementary Figs S4 and S5).

This paper uses a numerical ice-stream model to test and accurately replicate the known dynamic behaviour of a palaeo-ice stream, including temporary stabilizations over timescales longer than decades. Our dynamic simulations provide an improved understanding of the controls of marine ice-stream retreat and show that grounding lines can be close to stable on a reverse slope. Over and above the influence of bed topography described in the marine ice-sheet instability hypothesis[1–3], grounding-line stability is strongly controlled by subtle variations (for example 2–4 km narrowing over 20 km distance) in the width of the ice-stream trough. This effect would be enhanced further by buttressing in the presence of an ice shelf[2] and would be strongest in basins that are relatively narrow[25] and/or underlain by weak beds, such as the rapidly thinning Pine Island Glacier in West Antarctica[29].

We also show that ice-stream retreat is expected to be highly nonlinear and asynchronous to its forcing. This helps explain temporal and regional variations in the rate of mass loss being observed on present-day ice sheets[6] and why retreat patterns are not regionally synchronous following the LGM (ref. 23). The implications are that where modern grounding lines seem stable, mass loss may be continuing as part of a geometrically controlled response to a longer-term phase of ice-stream retreat triggered decades to millennia earlier. Furthermore, the importance of width fundamentally questions the widely used assumption that future grounding lines will retreat catastrophically across reverse-sloping beds[30] and provides a revised perspective on marine ice-stream stability. The lateral control and the longer-term upstream response suggest that interpretations of present rapid changes and future projections of ice-sheet stability should carefully integrate specific long-term ice-stream history and details of three-dimensional trough geometry.

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Author contributions

S.S.R.J. and A.V. contributed equally to this work. S.S.R.J. completed the numerical modelling and extended the model provided by A.V. S.S.R.J. wrote the first draft and all authors contributed to the analysis, interpretation and the writing of the paper. A.V., C.S., C.Ó.C. and C.D.H. conceived the idea and designed the research. S.J.L. carried out the mapping. C.D.H. and J.A.D. contributed chronological and geophysical data.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.S.R.J.

Competing financial interests

The authors declare no competing financial interests.