Subglacial sedimentary basins focus key vulnerabilities of the Antarctic ice-sheet

Lu Li (lu.li@research.uwa.edu.au)
School Of Earth Sciences, The University Of Western Australia https://orcid.org/0000-0001-6165-2828
Alan Aitken
The University of Western Australia https://orcid.org/0000-0002-6375-2504
Mark Lindsay
CSIRO Mineral Resources
Bernd Kulessa
Swansea University https://orcid.org/0000-0002-4830-4949

Article

Keywords:

Posted Date: December 10th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1117673/v1

Abstract

Antarctica preserves Earth's largest ice sheet which, in response to climate warming, may lose ice mass and raise sea level by several metres. The ice-sheet bed exerts critical controls on dynamic mass loss through feedbacks between water and heat fluxes, topographic forcing and basal sliding. Here we show that through hydrogeological processes, sedimentary basins amplify critical feedbacks that are known to impact ice-sheet retreat dynamics. We create a high-resolution subglacial bedrock classification for Antarctica by applying a supervised machine learning method to geophysical data, revealing the distribution of sedimentary basins. Sedimentary basins are found in the upper reaches of Antarctica's most rapidly changing ice streams, including Thwaites and Pine Island Glaciers. Hydro-mechanical numerical modelling reveals that where sedimentary basins exist, water discharge rate scales with the rate of ice unloading and the resulting hydrological instabilities are likely to amplify further retreat and unloading. These results indicate that the presence of a sedimentary bed in the catchment focuses instabilities that increase the vulnerability of the ice streams to rapid retreat and enhanced dynamic mass loss.

Main

Paleoclimate data indicate that change of the Antarctic ice-sheet is tightly coupled with climate forcing[1]. Under a warming future climate, Antarctic ice-sheet mass loss may cause a multi-meter contribution to sea level change on centennial timescales[2]. Although the current and near future Antarctic contribution to sea level rise is subordinate to other sources, satellite observations are consistent with accelerating mass loss over the last two decades[3]. Recent observations suggest that substantial and accelerating ice mass loss has occurred in several ice stream catchments in both West and East Antarctica[3]. However, in predictions of future sea level change, the effects of dynamic ice mass loss in Antarctica remain highly uncertain[4]. This uncertainty reflects in particular the identification of critical thresholds for dynamic mass loss, which are often associated with changing basal conditions.

Subglacial sedimentary basins are thick sediment accumulations and consolidated sedimentary rocks deposited and preserved beneath the ice-sheet. They are associated with different basal boundary conditions than a crystalline bedrock, because of their larger primary porosity, intrinsic permeability, lower relief surfaces, rheological stratification, and reduced mechanical strength. During glacial loading and unloading cycles, subglacial sedimentary basins may promote groundwater exchange flux[5-7] associated with advected heat flux[5,6]. Sedimentary basins may also provide a more readily eroded source of subglacial till[8].

With 99% of the continent covered by thick ice, the understanding of subglacial geology in Antarctica relies on geophysical data. Fig. 1 shows the current understanding of Antarctic bedrock type, which is driven by the interpretation of data from numerous individual studies (Supplementary Information 1.2). Direct constraints do not exist everywhere, and so the extents of sedimentary basins are undefined in many areas. A systematic understanding of basins has also been limited by the wide diversity of data and methods used and variable mapping criteria.

Here we develop the first sedimentary basin likelihood map for Antarctica using the supervised machine learning method Random Forest (RF)[10]. RF has proven to be a valid tool in lithology classification, which has high predictive performance with limited training information[11]. We apply this method to generate a likelihood model based on the current understanding of Antarctic bedrock type distribution. Evidence layers are sourced from the available continental-scale geophysical datasets including bedrock topography[9], gravity field[12], magnetic field[13], and their derivative products (Supplementary Information 1.3).

The output of RF analysis shows where a sedimentary basin classification (likelihood > 0.5) is predominant over a crystalline bedrock classification (likelihood < 0.5). The likelihood map (Fig. 2) shows the sedimentary rock distribution beneath the Antarctic ice-sheet with 75.11% classification accuracy by 10-fold block cross validation (Supplementary Information 1.5.3). It defines the major sedimentary basin extents, in stark contrast to crystalline bedrock dominated regions, and furthermore identifies some previously unknown basins.

Strikingly, the map defines sedimentary basins in some of Antarctica's most dynamic regions, including the Amundsen Coast and Siple Coast in West Antarctica and Wilkes Land and the Recovery region in East Antarctica, suggesting a significant influence on ice-sheet dynamics.

East Antarctic basins

In East Antarctica, major coast-perpendicular fault systems bound the sedimentary basin distribution in Wilkes Subglacial Basin[16]. We infer the presence of an extensive sedimentary basin preserved in the southern Wilkes Subglacial Basin, transitioning to less extensive cover in the north. This is consistent with a more complex history in the north, combining differential subsidence and glacial erosion[16]. For the major ice streams, our map shows sedimentary basins preserved beneath the Cook and Ninnis Glacier catchments, in contrast to a crystalline bed beneath the Mertz Glacier catchment (Fig. 3a).

The coast in Western Wilkes land is dominated by crystalline bedrock, however, the inland region contains broadly-distributed sedimentary basins including Aurora, Vincennes, Sabrina and Knox Subglacial Basins (Fig. 2). Ice mass loss in this region is concentrated on Denman, Totten and Vanderford Glaciers[20], with the sedimentary basins located in the upper catchments of these ice streams (Extended Data Fig. 1). The sedimentary basin distribution for the Totten Glacier catchment has been interpreted to represent repeated instability driven retreat over the region now possessing sedimentary basins[21]. As well as reverse bed slopes[21], fast retreat and readvance here may be exacerbated by hydrogeological feedbacks[6].

In the Recovery region, major basins are defined in the upper catchments of the Bailey, Slessor and Recovery Ice Streams, linking to coastal basins (Fig. 3b). Airborne radar observations are consistent with the presence of a subglacial hydrological system that originates at lakes in the upper Recovery Ice Stream, controlling its dynamics[22]. The broad basins we resolve are located beneath this active lake system, and could support the latter's interaction with a deep groundwater system. We also map two distinct sedimentary basins near the South Pole: The Pensacola-Pole Basin extending into the Foundation Ice Stream catchment, and a separate basin extending to the Wilkes Subglacial Basin (Fig. 2). The basins are associated with large numbers of subglacial lakes[18] and anomalously high geothermal flux near the South Pole Basin[23] potentially with implications for the dynamics of Foundation and Wilkes Land catchments.

The map resolves a dominant crystalline bedrock in central East Antarctica, including the Gamburtsev Subglacial Mountains, with surrounding basins resolved linked to the East Antarctic Rift System and Lambert Rift (Fig. 2). With moderate likelihood, sedimentary basins are inferred in the Dronning Maud Land sector with a sedimentary basin located in the West Ragnhild Trough, and another sedimentary basin inland, aligned with an inferred paleo-fluvial basin[24].

West Antarctic basins

In the Ross Embayment of West Antarctica, the map resolves widespread basin coverage with intervening basement ridges (Fig 2). Sedimentary basins continue from the Ross Sea, beneath the Ross Ice Shelf and, via the Siple Coast region, linking to the inland area of the Amundsen Embayment. The basin coverage is interrupted by volcanic rocks of the McMurdo Volcanic Complex with low sedimentary basin likelihood in front of and beneath the Ross Ice Shelf. Sedimentary basins are also preserved in the Weddell Sea sector from Robin Subglacial Basin to the inner Filchner-Ronne Ice Shelf. For the Institute Ice Stream, we observe fast ice flow over a sedimentary basin, with ice thinning occurring at the Robin Subglacial Basin

(Extended Data Fig. 1). The adjacent Möller Ice Steam shows a slower and stable ice flow over the crystalline bedrock. The Antarctic Peninsula geology is characterised by magmatic rocks intruding sedimentary basins[25], and our map shows large likelihood variations, reflecting the complexity in this area (Supplementary Information 1.5.3).

In the Siple Coast region (Fig. 3c), the map shows a sedimentary basin interspersed with extensive volcanoes[15], reflecting the volcanic-sedimentary nature of the West Antarctic Rift System[26]. The overlying ice streams are characterised by rapid changes in the ice-sheet state controled by the till property variations coupled with subglacial hydrology[27,28]. In the Bellingshausen Sea sector, a sedimentary basin is preserved in the Ferrigno Rift, interpreted to enhance the dynamics of the ice stream above[29]. In the Amundsen Sea region (Fig. 3d), the map shows a transition from sedimentary basin to crystalline bedrock on the inner continental shelf, recording paleo-ice stream history[30]. For Pine Island Glacier, the paleo-grounding line has undergone rapid retreat through the sedimentary basin and crystalline bed transition region due to high meltwater flux[30]. Our map shows moderate basin likelihood (~0.5) at the grounding line, but the upper catchment is clearly associated with a sedimentary basin. In Thwaites Glacier, we find the downstream side is dominated by a crystalline bed, while the upper ice stream preserves a broad sedimentary basin. The transition from sedimentary basin to a crystalline bed is coincident with a transition from a distributed subglacial hydrological system to one dominated by a basal network of channels[19]. The inversion of basal shear stress indicates the retreat of the grounding line could be triggered by subglacial water dynamics upstream[31]. For Pine Island and Thwaites Glaciers, subglacial hydrology and till supply are critical controls on ice flow that are dependent on sedimentary basins in the upper ice stream catchment.

Influence of sedimentary basins on ice-sheet dynamics

This new map of subglacial bedrock character shows that many of Antarctica's most rapidly changing catchments, including ice streams in the Amundsen, Wilkes, Recovery, and Siple Coast sectors, possess extensive sedimentary basins, particularly in their upstream portions. The environment of the ice-sheet bed, including till conditions, heat flux, and hydrology acts to define the dynamics of the overlying ice sheet: If the presence of sedimentary basins increases the likelihood of instabilities occurring, we may expect an enhanced likelihood of dynamic ice-sheet behaviour where basins exist.

Till conditions are essential in facilitating basal sliding, with many feedbacks with sediment sources, hydrology and ice-loading processes recognised[32]. In many cases, a weak till layer is thought to reduce the basal friction facilitating enhanced ice-sheet flow[33], whereas the lack of a weak till layer is commonly associated with much slower flow[34]. An important factor is a consistent supply of till in the so-called "till conveyor" which depends on the upstream erosion of bedrock[35]. In contrast to a crystalline bedrock, a sedimentary basin is mechanically weaker due to reduced competency and may also have layered structures leading to higher erodibility[36]. Consequently, the existence of sedimentary basins in the upper portions of ice streams may favour a sustained supply of subglacial till[8].

Subglacial hydrology is a critical factor in ice-sheet dynamics, with wet-based glaciers showing faster flow and enhanced basal sliding overall, compared to cold-based glaciers[37]. Subglacial hydrology also strongly impacts till conditions: The input of basal water commonly weakens a till layer, while the extraction of pore water consolidates it[38]. In addition, freshwater that flows across the grounding line influences ice shelf stability with feedbacks that affect grounded ice dynamics[17]. Finally, the circulation of water in subglacial aquifers may transport heat from depth to the ice-sheet bed, with impacts on till and ice rheology and hydrology[6].

The presence of permeable rocks at the ice-sheet bed therefore introduces the potential for interaction between the basal water system and deep groundwater aquifer systems[5-7]. In particular, ice-sheet retreat and unloading may lead to increased water flux at the ice-sheet bed[6] . We use a 2D Control Volume Finite Element Model[39] to investigate the potential impact of a permeable bed on water flux for retreat scenarios. We test the hypothesis that where a permeable bed exists in the upstream catchment, ice-sheet retreat causes a significant increase in basal water discharge rate relative to an entirely crystalline bed. Secondly we investigate the scaling between the grounding line retreat rate and the basal water discharge rate (Extended Data Fig. 2).

Our simulations indicate that during ice-sheet retreat water discharges into the basal water system due to ice-unloading. The subglacial vertical water flux is controlled by the permeability and thickness of the sedimentary strata. Our base scenario has a 3 km thickness sedimentary basin with vertical permeability of crystalline basement, confined unit (clay and shale) and aquifer (sandstone) at 10^{-19}, 10^{-17}, 10^{-15} m^2 respectively. Unloading over 10 ka with a grounding-line retreat rate of 130 m a^{-1} causes an additional mean subglacial water flux of up to 1.96 mm a^{-1} compare with crystalline basement only (Fig. 4a). Considering the mean basal melt rate for grounded ice sheet is 5.3 mm a^{-1} [40], this additional water flux from groundwater has a significant contribution to the hydrologic budget, as indicated previously for the Siple Coast ice streams, where up to 45% of flux may be groundwater derived[28]. We find increasing basal aquifer permeability and thickness facilitates higher groundwater flux rates during ice-sheet unloading, although extremely high permeability (e.g. in gravels or fractured rock aquifers) may sink major basal water into the groundwater system (Supplementary Information 2.3.1).

Increased water flux, as we indicate above, has further implications for both heat flux and till conditions. Water circulating in the sedimentary basin advects the geothermal heat from deeper aquifers to the ice-sheet bed. With a 60 mW m^{-2} bottom flux boundary condition, we model 2–5 mW m^{-2} higher heat flux due to groundwater discharge during the retreat phase (Supplementary Information 2.3.3), leading to a potential enhancement of basal melting (0.2–0.5 mm a^{-1}). In the presence of till, both water from enhanced basal melting, and water discharged from groundwater may weaken the till strength at the bed[38,41]. Finally, upward water flux may balance the gravitational weight of sediment causing sediment liquefaction[42]. Combined, these processes will reduce the basal friction to enhance the ice flow, promoting dynamic ice mass loss.

Crucially, high ice stream retreat rates may have even more marked effects on the magnitude of water flux (Fig. 4c-d). For a retreat rate of 300 m a^{-1}, approximately that observed for Thwaites Glacier[43], enhanced basal water flux of 5 mm a^{-1} is modelled, comparable to modelled basal melt rates in the upper Thwaites catchment[44]. A hypothetical fast retreat of the ice sheet (1,300 m a^{-1}) enhances basal water flux substantially (up to 20 mm a^{-1}) which may be substantial even in the lower catchments of fast retreating glaciers.

Our sedimentary basin map for Antarctica indicates that the fastest-changing ice catchments in East and West Antarctica possess sedimentary beds in their upper portions (Fig. 3), indicating that processes linked to sedimentary basins contribute significantly to catchment-scale ice dynamics. We model enhanced groundwater discharge into the ice-sheet bed where ice retreat is coupled with permeable aquifers upstream, so increasing subglacial water flux. Under moderate retreat scenarios with rates < 300 m a^{-1}, groundwater flux may be enhanced by up to 5 mm a^{-1}, comparable with average basal melt rates driven by geothermal heat flux for Antarctica[44]. While not insignificant, this is small in comparison to basal melt rates in fast-flowing glaciers, which may reach 20–100 mm a^{-1}[44]. However, in a fast retreat or collapse scenario with rates > 650 m a^{-1} the groundwater flux exceeds 10 mm a^{-1}, potentially sustaining a significant source of subglacial water even in high basal melt rate environments. The enhanced flux caused by retreat feeds back into dynamic processes affecting basal sliding including a weakened till layer, enhanced heat flux and enhanced basal melt rate and also potential destabilisation of ice shelves[17]. We propose that the instabilities caused by enhanced subglacial water supply from sedimentary aquifers, triggered by rapid ice-sheet retreat, are a crucial mechanism controlling the vulnerability of the Antarctic ice-sheet.

Methods

Sedimentary basin mapping with Random Forest prediction

The RF prediction algorithm[10] is built based on an ensemble of decision trees[45]. The randomness of RF is guaranteed by the uniqueness of each decision tree. Every tree in RF is constructed by a bootstrapped sample method (select nearly 2/3 of total training data with replacement), and grew by a random subset of evidence layer at each split. For bedrock type classification, each tree "votes" for the bedrock class, with the final result is assembled by the result of all uncorrelated trees. In each location, the averaged vote represents the probability of each bedrock class being present. For the binary bedrock type classification problem in this study, a 0.5 likelihood is a natural boundary representing sedimentary basin or the crystalline bedrock. The R core 4.0.2 and package randomForest[46] was used to perform RF analysis. For further details of the RF method, see the Supplementary Information 1.

Hydro-mechanical model

We use Control Volume Finite Element Model CVFEM_Rift2D to simulate the subglacial water system and heat transfer within a sedimentary basin in response to ice-sheet loading and unloading[39]. The model setting of hydro-mechanical modelling is listed in the supplementary information 2. Codes and further details of using CVEFM_Rift2D can be accessed by the original paper[39].

Code and Data availability

The code and data for RF classifaction can be access at https://github.com/LL-Geo/ANT_SEDI .

Declarations

Acknowledgements

The authors thanks Mathieu Morlighem for providing basal friction data. This research was supported by the Australian Research Council Special Research Initiative, Australian Centre for Excellence in Antarctic Science (Project Number SR200100008). L.L. was supported by China Scholarship Council–The University of Western Australia joint Ph.D. scholarship (201806170054). M.D.L was supported by ARC DECRA DE190100431. We thank Martin Siegert for his constructive comments on an earlier version of the manuscript.

Author Contributions

L.L. led the research; L.L., A.R.A.A. and M.D.L conceived the scope and design of the research. L.L. and A.R.A.A. led the writing of the manuscript. L.L., A.R.A.A. and B.K. discussed and wrote the ice sheet dynamics section. M.D.L and A.R.A.A. advised L.L. in performing Random Forest classifcation. A.R.A.A advised L.L. in performing hydromachinical modelling. All authors contributed ideas and to the writing of the manuscript.

Corresponding author

Correspondence to Lu Li (lu.li@research.uwa.edu.au).

Competing interests

The authors declare no competing interests.

References

1 Dutton, A. *et al.* Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* **349** (2015).

2 DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**, 591-597 (2016).

3 Rignot, E. *et al.* Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proc. Nat. Acad. Sci. U.S.A.* **116**, 1095-1103 (2019).

4 Noble, T. L. *et al.* The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and Future. *Rev. Geophys.* **58**, doi:10.1029/2019RG000663 (2020).

5 Siegert, M. J. *et al.* Antarctic subglacial groundwater: a concept paper on its measurement and potential influence on ice flow. *Geol. Soc. Spec. Pub.* **461**, 197-213 (2018).

6 Gooch, B. T., Young, D. A. & Blankenship, D. D. Potential groundwater and heterogeneous heat source contributions to ice sheet dynamics in critical submarine basins of E ast A ntarctica. *Geochem. Geophys. Geosyst.* **17**, 395-409 (2016).

7 Lemieux, J. M., Sudicky, E., Peltier, W. & Tarasov, L. Dynamics of groundwater recharge and seepage over the Canadian landscape during the Wisconsinian glaciation. *J. Geophys. Res. Earth Surface* **113** (2008).

8 Bell, R. E. *et al.* Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations. *Nature* **394**, 58, doi:10.1038/27883 (1998).

9 Morlighem, M. *et al.* Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nat. Geosci.* **13**, 132-137, doi:10.1038/s41561-019-0510-8 (2020).

10 Breiman, L. Random Forest. *Machine Learning* **45**, 5-32, doi:10.1023/a:1010933404324 (2001).

11 Kuhn, S., Cracknell, M. J. & Reading, A. M. Lithological mapping in the Central African Copper Belt using Random Forests and clustering: Strategies for optimised results. *Ore Geol. Rev.* **112**, 103015 (2019).

12 Scheinert, M. *et al.* New Antarctic Gravity Anomaly Grid for Enhanced Geodetic and Geophysical Studies in Antarctica. *Geophys. Res. Lett.* **43**, 600-610, doi:10.1002/2015GL067439 (2016).

13 Golynsky, A. V. *et al.* New Magnetic Anomaly Map of the Antarctic. *Geophys. Res. Lett.* **45**, 6437-6449, doi:10.1029/2018gl078153 (2018).

14 Rignot, E., Jacobs, S., Mouginot, J. & Scheuchl, B. Ice-shelf melting around Antarctica. *Science* **341**, 266-270 (2013).

15 de Vries, M. v. W., Bingham, R. G. & Hein, A. S. A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. *Geol. Soc. Spec. Pub.* **461**, 231-248 (2018).

16 Frederick, B. C. *et al.* Distribution of subglacial sediments across the Wilkes Subglacial Basin, East Antarctica. *J. Geophys. Res. Earth Surface* **121**, 790-813, doi:doi:10.1002/2015JF003760 (2016).

17 Le Brocq, A. M. *et al.* Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nat. Geosci.* **6**, 945-948 (2013).

18 Wright, A. & Siegert, M. A fourth inventory of Antarctic subglacial lakes. *Antarct. Sci.* **24**, 659 (2012).

19 Schroeder, D. M., Blankenship, D. D. & Young, D. A. Evidence for a water system transition beneath Thwaites Glacier, West Antarctica. *Proc. Nat. Acad. Sci. U.S.A.* **110**, 12225-12228 (2013).

20 Smith, B. *et al.* Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science* **368**, 1239-1242 (2020).

21 Aitken, A. R. *et al.* Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion. *Nature* **533**, 385-389, doi:10.1038/nature17447 (2016).

22 Diez, A. *et al.* Basal Settings Control Fast Ice Flow in the Recovery/Slessor/Bailey Region, East Antarctica. *Geophys. Res. Lett.* **45**, 2706-2715, doi:10.1002/2017gl076601 (2018).

23 Jordan, T. *et al.* Anomalously high geothermal flux near the South Pole. *Sci. Rep.* **8**, 1-8 (2018).

24 Eagles, G. *et al.* Erosion at extended continental margins: Insights from new aerogeophysical data in eastern Dronning Maud Land. *Gondwana Res.* **63**, 105-116, doi:10.1016/j.gr.2018.05.011 (2018).

25 Burton-Johnson, A. & Riley, T. R. Autochthonous v. accreted terrane development of continental margins: a revised in situ tectonic history of the Antarctic Peninsula. *J. Geol. Soc.* **172**, 822-835 (2015).

26 Blankenship, D. D. *et al.* Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability. *Nature* **361**, 526-529 (1993).

27 Bougamont, M. *et al.* Reactivation of Kamb Ice Stream tributaries triggers century-scale reorganization of Siple Coast ice flow in West Antarctica. *Geophys. Res. Lett.* **42**, 8471-8480 (2015).

28 Christoffersen, P., Bougamont, M., Carter, S. P., Fricker, H. A. & Tulaczyk, S. Significant groundwater contribution to Antarctic ice streams hydrologic budget. *Geophys. Res. Lett.* **41**, 2003-2010 (2014).

29 Bingham, R. G. *et al.* Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts. *Nature* **487**, 468-471 (2012).

30 Nitsche, F. O. *et al.* Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica. *The Cryosphere* **7**, 249-262 (2013).

31 Sergienko, O. V. & Hindmarsh, R. C. Regular patterns in frictional resistance of ice-stream beds seen by surface data inversion. *Science* **342**, 1086-1089 (2013).

32 Evans, D., Phillips, E., Hiemstra, J. & Auton, C. Subglacial till: formation, sedimentary characteristics and classification. *Earth-Science Reviews* **78**, 115-176 (2006).

33 Alley, R. B., Blankenship, D. D., Bentley, C. R. & Rooney, S. Deformation of till beneath ice stream B, West Antarctica. *Nature* **322**, 57-59 (1986).

34 Siegert, M. J. *et al.* Subglacial controls on the flow of Institute Ice Stream, West Antarctica. *Ann. Glaciol.* **57**, 19-24 (2016).

35 Alley, R. B. *et al.* How glaciers entrain and transport basal sediment: physical constraints. *Quat. Sci. Rev.* **16**, 1017-1038 (1997).

36 Phillips, E., Everest, J. & Diaz-Doce, D. Bedrock controls on subglacial landform distribution and geomorphological processes: Evidence from the Late Devensian Irish Sea Ice Stream. *Sediment. Geol.* **232**, 98-118 (2010).

37 Bell, R. E. The role of subglacial water in ice-sheet mass balance. *Nat. Geosci.* **1**, 297-304 (2008).

38 Christoffersen, P. & Tulaczyk, S. Response of subglacial sediments to basal freeze-on 1. Theory and comparison to observations from beneath the West Antarctic Ice Sheet. *J. Geophys. Res. Solid Earth* **108** (2003).

39 Zhang, Y. *et al.* Hydromechanical impacts of Pleistocene glaciations on pore fluid pressure evolution, rock failure, and brine migration within sedimentary basins and the crystalline basement. *Water Resour. Res.* **54**, 7577-7602 (2018).

40 Pattyn, F. Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth Planet. Sci. Lett.* **295**, 451-461 (2010).

41 Flowers, G. E. & Clarke, G. K. A multicomponent coupled model of glacier hydrology 1. Theory and synthetic examples. *J. Geophys. Res. Solid Earth* **107**, ECV 9-1-ECV 9-17 (2002).

42 Boulton, G., Lunn, R., Vidstrand, P. & Zatsepin, S. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: part 1—glaciological observations. *Quat. Sci. Rev.* **26**, 1067-1090 (2007).

43 Konrad, H. *et al.* Net retreat of Antarctic glacier grounding lines. *Nat. Geosci.* **11**, 258-262 (2018).

44 Joughin, I. *et al.* Basal conditions for Pine Island and Thwaites Glaciers, West Antarctica, determined using satellite and airborne data. *J. Glaciol.* **55**, 245-257 (2009).

45 Breiman, L., Friedman, J., Stone, C. J. & Olshen, R. A. *Classification and regression trees*. (CRC press, 1984).

46 Liaw, A. & Wiener, M. Classification and Regression by randomForest. *R News* **2**, 18-22 (2002).

Figures

Figure 1

Limited current understanding of subglacial bedrock type from bedrock outcrop, seismic studies, and regional potential field interpretations. The underlying surface is the topography from BedMachine Antarctica9. The black line shows coastline and grounding line. The turquoise line shows offshore seismic measurements archived at Antarctic Seismic Data Library System (SDLS). Note the lack of information about sedimentary basins in the interior of East Antarctica, and also below major ice shelves (RIS and FRIS). Labels: AIS, Amery Ice Shelf; ASB, Aurora Subglacial Basin; AST, Adventure Subglacial Trench; CT, Central Trough; DML, Dronning Maud Land; EB, Eastern Basin; FR, Ferrigno Rift; FRIS, Filchner–Ronne Ice Shelf; GSM, Gamburtsev Subglacial Mountains; KSB, Knox subglacial basin; LV, Lake Vostok; MBL, Marie Byrd Land; PPB, Pensacola Pole Basin; RB, Recovery Basin; RIS, Ross Ice Shelf; RSB, Robin Subglacial Basin; SSB, Sabrina Subglacial Basin; TAM, Transantarctic Mountains; VLB, Victoria Land Basin; VSB, Vincennes Subglacial Basin; WRT, West Ragnhild Trough; WSB, Wilkes Subglacial Basin.

Figure 2

Sedimentary basin likelihood map from RF classification. The likelihood map shows wide distributed sedimentary basins beneath the Antarctic ice-sheet. The black lines delineate the major glacier catchments14. Yellow triangles indicate potential volcanoes15 interspersed with sedimentary basins in West Antarctica. Dashed boxes marks regions shown in Fig. 3.

Figure 3

Sedimentary basin likelihood map focusing on key ice streams. a-d, Sedimentary basin likelihood map for four highly dynamic regions. a, Wilkes Subglacial Basin. b, Recovery Basin. c, Siple Coast Region. d, Amundsen Sea Embayment. Map locations are shown by the dashed boxes in Fig. 2.The white lines delineate the major glacier catchments14. The green line indicates modelled subglacial water flux (>0.25 m3s-1)17 and stars show subglacial lakes18. The black dashed box in d demarcates the water transition system in Thwaites Glacier19. Labels: WIS, Whillans Ice Stream; MIS, Mercer Ice Stream; KIS, Kamb Ice Stream; BIS, Binschadler Ice Stream; MacIS, MacAyeal Ice Stream; TG, Thwaites Glacier; PIG, Pine Island Glacier; CISG, Cook Ice Shelf Glaciers; NG, Ninnis Glacier; MG, Mertz Glacier; BaIS, Bailey Ice Stream; RG, Recovery Glacier; SG, Slessor Glacier; SFG, Support Force Glacier.

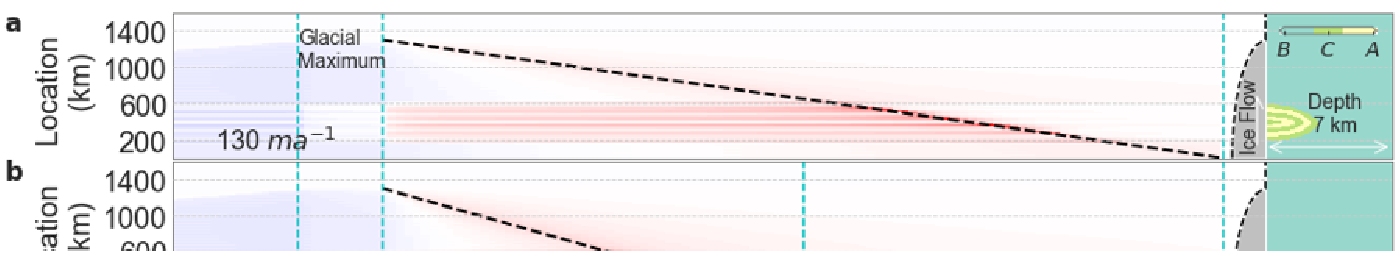

Figure 4

Groundwater discharge through time for moderate to fast retreat rates. a-d, Vertical water flux at the ice-sheet bed associated with various ice-sheet retreat rates. a, 130 m a-1. b, 260 m a-1. c, 650 m a-1. d, 1,300 m a-1. Black dashed line shows the location of the ice-sheet margin with subglacial water flux imaged below the line. Positive vertical water flux indicates groundwater discharge while negative vertical water flux indicates recharge. We show sedimentary basin geometry at the right. Aquifer unit A has horizontal permeability κx =10-14 m2 and vertical permeability κz =10-15 m2; the confined unit C has κx =10-16 m2 and κz =10-17 m2; the crystalline bedrock basement B has κx = κz =10-19 m2. The ice expands over 20 ka to glacial maximum at 1300 km, before initiating retreat. The grey area shows the parabolic ice-sheet geometry at glacial maximum. e, Mean subglacial water flux changes relative to a crystalline bedrock for different retreat rates. The permeable bed promotes enhanced discharge from the upstream basin during ice-sheet retreat and the mean discharge-rate scales with retreat rate.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- VerticalwaterfluxduringglaciercircleBasepermeabilitycase1013m2.mp4
- VerticalwaterfluxduringglaciercircleBasepermeabilitycase1015m2.mp4
- Supplymentinformation.docx
- ExtendedData.docx